
Air view north of the Ambrosia Lake area showing some of the principal mines and mills and the northwest-dipping stratigraphy from the Upper Triassic Chinle Formation in the foreground to the Upper Cretaceous Hosta Sandstone Member of the Mesaverde Group on the skyline. Pueblo Photo Service photo.

MEMOIR 15

# Geology and Technology of the Grants Uranium Region

*Prepared by*
*The Society of Economic Geologists*
*Vincent C. Kelley, General Chairman*
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# *Contents*


*Page*

Air View North of the Ambrosia Lake Area *Frontispiece*

PREFACE, *Vincent* C. *Kelley* .............................

HISTORY OF EXPLORATION, *Paul* E. *Melancon* .......................................................................... 3

REGIONAL AND LOCAL STRATIGRAPHY OF URANIUM-BEARING ROCKS, *Lowell S. Hilpert* .......................................................................................................... 6

TECTONIC SETTING, *Vincent* C. *Kelley* 19

MAP SHOWING THE GENERAL STRUCTURAL FEATURES of the Grants area and the areal distribution of the known uranium ore bodies in the Morrison Formation, *Robert* E. *Thaden and Elmer S. Santos* ..........................................................................between pp. 20 and 21

MINERALOGY, *H.* C. Granger 21

ALTERATION OF MORRISON SANDSTONE, S. *Ralph Austin* .................................................. 38

GEOLOGY OF THE BLACK JACK NO. 1 MINE, SMITH LAKE AREA, M. *E. MacRae* 45

GEOLOGY OF THE BLACK JACK NO. 2 MINE, SMITH LAKE AREA, *William G. Hoskins* 49

RELATION OF ORE DEPOSITS TO THE STRATIGRAPHY OF THE AMBROSIA LAKE-AREA, E. S. *Santos* ........................................................................................................ 53

GEOLOGY OF THE DYSART NO. 1 MINE, AMBROSIA LAKE AREA, R. *J.* Cronk 6o

GEOLOGY OF THE HOMESTAKE-SAPIN URANIUM DEPOSITS, AMBROSIA LAKE AREA, *Walter Gould, Robert B. Smith, Stephen P. Metzger, and Paul E. Melancon*................. 66

GEOLOGICAL SETTING OF AN ANOMALOUS ORE DEPOSIT IN THE SECTION 30 MINE, AMBROSIA LAKE AREA, T. A. *Clary*, C. M. *Mobley, and G. F. Moulton*, Jr. . . . 72

URANIUM AND VANADIUM MINERALS OCCURRING IN SECTION 22 MINE, AMBROSIA LAKE AREA, R. G. *Corbett* 8o

GEOLOGY AND ORE DEPOSITS OF THE SOUTHEASTERN PART OF THE AMBROSIA LAKE AREA, *George W. Hazlett and Justin Kreek* ................................................... 82

Page

GEOLOGY AND ORE DEPOSITS OF THE ANN LEE MINE, AMBROSIA LAKE AREA, *John B. Squyres* .......... 90

GEOLOGY AND ORE DEPOSITS OF THE SANDSTONE MINE, SOUTHEASTERN AMBROSIA LAKE AREA, *Gary F. Harmon and Paul S. Taylor* .......... 102

GEOLOGY AND ORE DEPOSITS OF THE CLIFFSIDE MINE, AMBROSIA LAKE AREA, *Dean S. Clark and Stuart R. Havenstrite* .......... *i* o8

GEOLOGY OF THE MARQUEZ MINE, AMBROSIA LAKE AREA, R. *J. Weege* .......... *117*

URANIUM DEPOSITS OF THE POISON CANYON ORE TREND, GRANTS DISTRICT, *Irving Rapaport* 122

URANIUM DEPOSITS IN THE TODILTO LIMESTONE OF THE GRANTS DISTRICT, E. D. *McLaughlin, Jr* 136

LIMESTONE REEFS AS AN ORE CONTROL IN THE JURASSIC TODILTO LIMESTONE OF THE GRANTS DISTRICT, *Bobbie* L. *Perry* .......... 15o

GEOLOGIC LIMITATIONS ON THE AGE OF URANIUM DEPOSITS IN THE LAGUNA DISTRICT, *Robert H. Moench* 157

GEOLOGY OF THE JACKPILE MINE AREA, *Dale F. Kittel* .......... 167

GEOLOGY OF THE WOODROW BRECCIA PIPE, *Ernest T. Wylie* .......... *177*

SULFUR ISOTOPES AND BIOGENIC ORIGIN OF URANIFEROUS DEPOSITS OF THE GRANTS AND LAGUNA DISTRICTS, *M.* L. *Jensen* .......... *t* 82

ORE PROCESSES, R. A. *Laverty, W. R. Ashwill, W.* L. *Chenoweth, and* D. L. *Norton* .......... *191*

STRUCTURE AND VOLCANISM, GRANTS RIDGE AREA, *Paul F. Kerr and J. Thomas Wilcox* 205

POTASSIUM—ARGON AGES OF VOLCANIC ROCKS NORTH OF GRANTS, W. A. *Bassett, P. F. Kerr,* 0. A. *Schaeffer, and* R. W. *Stoenner* .......... 214

GROUND WATER IN THE VICINITY OF THE JACKPILE AND PAGUATE MINES, *George A. Dinwiddie* 217

GROUND WATER IN THE GRANTS DISTRICT, *Edward* C. *John and S. W. West* .......... 219

URANIUM LOGGING TECHNIQUES, W. A. *Linton* .......... 222

*Page*

ESTIMATION OF URANIUM ORE RESERVES BY STATISTICAL METHODS AND A DIGITAL COMPUTER, W. D. *Grundy and Robert J. Meehan* .............................................. 234

URANIUM MINING IN THE GRANTS DISTRICT, *I.* M. *Gay* .................................................... 244

PRODUCTION GEOLOGY METHODS AT THE KERMAC MINES, *Fred* C. *Hohne*

SUBSIDENCE AND PILLAR RECOVERY IN THE WEST AREA OF THE MARQUEZ MINE, *Glen* C. *Johnston* 256

MINE SAFETY PROBLEMS, *H. J. Abbiss* 264

RUDIMENTS OF URANIUM ORE METALLURGY, *Dale* C. *Matthews* .................................... 268

GROWTH AND PRODUCTION, *Ward E. Ballmer* ......................................................................... *27o*

INDEX 273

# *Preface*

The field conference for which this memoir is compiled was sponsored by the Society of Economic Geologists. At a meeting of the Council of the Society in the fall of 1961, it was decided to hold a Uranium Field Conference in the Grants region of New Mexico, and I was asked to proceed with arrangements. The conference appears to have been conceived by Charles F. Park, Jr., and James P. Pollock, for in a letter of June 15, 1961, to Mr. Park, Mr. Pollock outlined in considerable detail the fine opportunities for such a field trip and conference. The final arrangements and scheduling turned out to be essentially those of the original proposal.

In the beginning, a guidebook of road logs and short papers was considered for the occasion. However, because there already exist several guidebooks for the area, it was decided to assemble only papers. (Guidebooks with road logs and general geologic papers of the area are as follows:

Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona, Second Field Conference, New Mexico Geological Society, 1951.

Road log from Albuquerque, New Mexico, to Grants Uranium district, Rocky Mountain Section, Geological Society of America and New Mexico Geological Society, 1956.

Geology of southwestern San Juan Basin, Second Field Conference, Four Corners Geological Society, 1957.

These publications contain numerous references to other geologic literature of the area.)

In the compilation of this memoir, an effort was made to get as many papers as possible from people who have worked recently in the area. An effort was also made to include most phases of the economic geology and related subjects. Thus, papers on mining and safety bring out special problems related to lithology, ground water, ore body forms, and depth of mining. A paper on milling not only outlines the special uranium processes but also points up the relationships to ore and rock compositions. Papers on ground water are included, but a significant paper on waste disposal problems was lost by a late personnel shift in the district. Several papers describe the unusual growth of and exploration in the district.

The Grants Uranium Region, as used for this memoir, includes the entire area of deposits from Gallup on the west to the western edge of the Rio Grande trough on the east, a distance of about r r o miles. The region is also referred to as the Grants mineral belt. Neither favorable host rocks nor deposits are continuous throughout this distance, but there are several places where special stratigraphy or structure has resulted in large accumulations of uranium in areas of favorable exposures. The principal areas, from west to east, are Gallup, Churchrock, Smith Lake, Ambrosia Lake, Grants, and Paguate or Jackpile. These areas are grouped into three mining districts: Gallup, Grants, and Laguna.

The Grants region experienced phenomenal development, growing from practically nothing in 1951 to a position of great national importance by 1955. There are several stories about the discoveries that culminated in the big development of the early fifties. Paddy Martinez, an Indian, is generally credited with bringing in the "find" that triggered the rush and boom in 1951. However, I am sure that many of the "old timers" in the Grants and Gallup districts were aware of the uranium minerals long before. As one who almost rates the "old timer" tag, I like to recall the winter of 1937 when I often partook of the fine family-style meals at Mrs. Whitesides' cafe in Grants. Mr. Whitesides, a prospector at times, had recently passed away. Mrs. Whitesides often brought samples from her husband's collection for me to see, and on one occasion it was a good-sized, canary-yellow sample which I identified as carnotite and added, ironically, "it has no value." Again, about 195o, a very large prospector who came to see me about things in general and some of the old days in particular related how he and others prospected the carnotite beds near Gallup about 192o. It is also reported that federal geologists had examined reported deposits in the Grants district in the early forties. No one really knows who first discovered the Grants uranium, and it is possible that before the white man, the Indians used it locally for pigment. It really is not surprising that such abundant stuff was known by many before 1951.

Numerous minerals are mentioned or described, and not including the common rock minerals, they number some 76 in this memoir.

The Todilto Limestone deposits and Anaconda's Jackpile sandstone deposit were discovered for mining in 1951. The rapid rise of the Grants district was presaged by the quick completion of the Bluewater limestone mill in 1953. By 1954, as many as 16 producers were shipping to the mill. In 1955, the subsurface Ambrosia Lake—Westwater Canyon deposits were discovered, and Anaconda's sandstone mill was completed. By 1956, New Mexico's mining of uranium ore had risen to 1,105,000 tons valued at $24,086,000, and the Atomic Energy Commission credited New Mexico with 41 million tons of uranium ore reserves, or two thirds of the U.S. total. In early 1958, the first of the Ambrosia Lake sandstone mills was put into operation. By 1959, nearly all the State's prodution (3,269,826 tons valued at $53,463,000) came from the Grants region, and the reserves were estimated by the Atomic Energy Commission at 55,000,000 tons, or 63 percent of the nation's total. Also by 1959, the present six mills were well into production with a rated capacity of 10,500 tons a day. The Kermac mill alone in 1961 was credited with a $U_3O_8$ recovery of nearly 20 percent of the U.S. total. The cost of these mills is listed at about $62,344,000.

As General Chairman of the Conference, and on behalf of the Society of Economic Geologists, I wish to express thanks to the many authors who, often with full duties elsewhere, rose so unhesitatingly to the task of preparing their papers. I wish also to express appreciation to the administrative personnel of the companies and institutions who encouraged or aided the geologists in the submission of papers. In particular, I wish to mention here Charles E. Anderson and Hugh D. Miser of the U.S. Geological Survey; Allen E. Jones and David D. Baker of the Grand Junction Operations Office, U.S. Atomic Energy Commission; Albert J. Fitch of The Anaconda Company; J. L. Robison of Kermac Nuclear Fuels Corportion; Langan Swent of Homestake—Sapin Partners; C. N. Holmes of Phillips Petroleum Corporation; James P. Pollock of Calumet and Hecla, Inc.; Robert Kirchman of KSN Company, Inc.; and Charles C. Towle of United Nuclear Corporation.

Finally, there is a group of men to whom credit for many of the papers and the general organization of the memoir and conference must go. These men, constituting a steering committee for the Conference, are David C. Arnold, Walter Gould, Fred C. Hohne, Dale F. Kittel, Robert A. Laverty, Paul E. Melancon, E. D. McLaughlin, Jr., Irving A. Rapaport, Ted M. Rizzi, John B. Squyres, and Charles C. Towle.

VINCENT C. KELLEY
General Chairman,
Uranium Field Conference

# *History of Exploration*

PAUL E. MELANCON

## INTRODUCTION

The rapid development and practical utilization of new exploration techniques and tools have played an important part in the evolution of the Grants uranium region. Methods used to explore for and define the deposits of the district included rim walking with and without radiation detectors, radiometric traverses, geobotanical sampling, airborne radiometric reconnaissance using fixed-wing aircraft and helicopters, test pitting, trenching, rim stripping, wagon drilling with percussion drills, diamond-core drilling, rotary noncore drilling used in conjunction with natural radioactivity and electric logging, and extensive long-hole drilling from underground workings. Each of the methods has been at least partially responsible for the discovery of a mineable deposit.

## DISCOVERY

Paddy Martinez, a Navajo Indian prospector, is responsible for the discovery that was to develop into the most prolific uranium-producing district in the world. Although his discovery was made in 195o, uranium minerals that were known to occur near Grants had been recognized in the early twenties *(Preface)* and mapped on the outcrop in 1948 (Smith, 1954). The minerals were given very little consideration at the time because of their oddity and their apparently limited volume and association with a limestone in 1948.

Martinez's tyuyamunite discovery was from a Todilto Limestone outcrop in sec. 19, T. 13 N., R. 10 W. at the base of Haystack Butte on property owned by the Santa Fe Pacific Railway Company, a land-owning subsidiary of the Atchison, Topeka, and Santa Fe Railway Company. The railway established a mining subsidiary, Haystack Mountain Development Company, and initiated an extensive evaluation and exploration program. They were soon joined by The Anaconda Company and many local individuals.

Uranium has since been found in commercially important quantities in the Dakota Sandstone and in the Brushy Basin Shale and Westwater Canyon Members of the Morrison Formation.

Reconnaissance mapping of the Jurassic outcrops from Grants to Gallup was undertaken by the Denver Exploration Branch of the U.S. Atomic Energy Commission in 1951, and the results were quickly published in March 1952 (Rapaport, Hadfield, and Olson, 1952) for use by parties interested in the local search for uranium.

## TODILTO LIMESTONE DEPOSITS

Exploration of the discovery area was undertaken by sinking 6 x 6-foot test pits on 100-foot centers through the Todilto Limestone. Bulk samples from the pits were taken at two-foot intervals, logged, crushed, sampled, and assayed (Towle and Rapaport, 195z).

Test-pitting soon yielded to exploration by wagon drills. Samples of the percussion drill cuttings were collected in goatskin bags attached to a Tee in the surface casing. The samples were radiometrically and chemically assayed for uranium in Haystack Mountain Development Company's own laboratory.

While evaluation of the odd-numbered sections extending from Haystack Butte to the San Mateo road (New Mexico Highway 53) was being carried out by the railway, The Anaconda Company was exploring the Todilto bench east of the San Mateo road. In addition to test pits and wagon drills, Anaconda used trenches, rim stripping by bulldozers, and core drills to explore for and to delineate deposits.

As physical exploration work proceeded, and the deposits began to take shape, ideas concerning genesis and reasons for localization were presented. One of the first geologic associations that received attention was the apparent relationship between uranium deposits and the broad, gentle warping indicated by mapping the Todilto—Entrada contact along the rim from Haystack Butte to the San Mateo road. Th largest known deposits seemed to occur in the upwarped areas, while the downwarped areas appeared to be less favorable. The areas of relative favorability indicated by these observations were still very large when compared to the size of the deposit being developed.

Studies made by Ellsworth and Mirsky (1952) reduced the size of the apparently favorable structures to fracturing and folding that could be mapped from outcrops or information from widely spaced drill holes on a single property. Intraformational folds were recognized at this time (Rapaport, Hadfield, and Olson; Ellsworth and Mirsky), but the role of these features as important localizing structures was not yet fully apparent. The eventual knowledge that these were important localizing structures did little to aid exploration from the surface because the folds have nearly the same areal extent as the ore bodies.

At this same time, the possible source of the uranium was a much discussed subject. The presence of fluorite and barite together with abundant nearby volcanic activity suggested to some a hydrothermal source. Others believed that the uranium was leached from volcanic debris in the Brushy Basin Shale and redeposited in the Todilto. The question is still without a completely satisfactory answer.

As exploration depths began to exceed 150 feet, the wagon drill was replaced by the rotary shot-hole drill. A tool that proved to have great versatility, it could drill deeper, faster, and at lower cost; it could be used to cut cores if necessary; and either compressed air or water could be used as a circulating medium to clear the cuttings from the hole.

common practice in drillin&on the Todilto bench is to use water and d ril ing mud whi l e penetrating the unconsolidated blow sand, the n dry the hole and complete it using compressed air. This method has several advantages, among them the need to haul less drilling water, faster penetration rates when using air, and cleaner, more reliable cuttings from the Todilto.

With the introduction of the rotary drill and deeper drilling came more extensive use of radioactivity logs as a means of determining the tenor of mineralization cut by the drill holes. The first generally used equipment consisted of a Geiger counter with a long cable; those manufactured by Gordon Babbel were most common. The Geiger tube was raised and lowered in the hole by a hand reel, and readings taken every six inches or one foot at the operator's discretion. An automatic recording device was eventually incorporated into the equipment, but had very limited use in the Grants district before it was replaced by the more sophisticated truck-mounted logging equipment.

Exploration for and discovery of ore bodies in the Todilto is still being successfully carried on in spite of the more glamorous discoveries in the Morrison Formation.

## MORRISON FORMATION DEPOSITS

### POISON CANYON AREA

The initial uranium discovery in the Morrison Formation was made in 1951 in sec. 19, T. 13 N., R. 9 W. in Poison Canyon. The area derived its named from the deadly effect the abundant "loco weed," *Astragalus*, had on cattle and sheep entering the canyon. This selenium-absorbing weed was later recognized as a ossible uide to uranium de osits (Cannon, 1953).

Soon after the Poison Canyon discovery, the Blue Peak deposit was located high on the rim of the adjoining sec. 24, T. 13 N., R. o W. It appears that this was a small remnant of a much larger deposit that had been eroded away. The name *Poison Canyon sandstone* was first applied to the unit in which these ore bodies occurred. Although the name has since been applied to similar sandstone units that occur in the same stratigraphic position, 100 to 160 feet below the base of the Dakota Sandstone, it is extremely doubtful that all these units are actually continuations of the original.

An adit and connecting drifts driven into a small remnant of Morrison sandstone lying south of the Dakota rim made the Poison Canyon mine the first underground operation in the Grants district. It was opened in 1951. Subsequent drilling to the east delineated an ore body large enough to warrant stripping some 5o feet of consolidated overburden. This eastward extension has since been developed into the Poison Canyon trend that now extends more than four miles to the east, and contains the Mesa Top, Malpais, Dog, Flea, Doris, and Marquez ore bodies.

### LAGUNA DISTRICT

At this same time, The Anaconda Company was conducting an extensive airborne radiometric reconnaissance program that resulted in the discovery north of Laguna, New Mexico, of what has become the largest uranium mine in the world, the Jackpile and associated ore bodies..

Initial exploration and development of the Jackpile was done almost exclusively with core drills, and before the stripping operation was decided upon, two adits were driven into the ore body to check the drilling results. Bulk samples taken from the tunnels and raises were put through the mill to test the amenability of the ores.

The presence of a diabase sill in the ore body added a great deal of the fuel to the h drothermal versus origin controversies. Later etas e work dehmtely established that the sill was later than (Hilpert and Moench, 1960).

### AMBROSIA LAKE AREA

Louis Lothman became responsible for the initial uranium discovery in the Ambrosia Lake area in the spring of 1955 when he found that cuttings from the Morrison section of an abandoned oil test were radioactive. He then proceeded to drill a test hole downdip and north of the abandoned drill site (Birdseye, 1957). The wildcat hole encountered mineralization in the Westwater Canyon Member of the Morrison Formation, and the extensive drilling that followed established what was to become the Dysart No. 1 ore body and first mine in the Ambrosia Lake area.

The location of this discovery on the flank of the obvious Ambrosia dome created more than a little interest in lands surrounding the structure and sent geologists scurrying vainly in search of similar structures. The structural association also brought out many ideas concerning localization of the Ambrosia Lake deposits (Birdseye; Zitting et al., 1957).

Since the amount of land immediately surrounding the dome was limited, latecomers had to take leases and stake claims on the remaining land along the Mancos bench. Most of those that acquired land east of the Ambrosia dome were well rewarded, and those to the west were generally disappointed

Exploration activity reached its height during 1956 when more than zoo drilling rigs were in operation in what is now the Ambrosia Lake area. Noncore rotary drills made up the great majority of the operating rigs. Conventional core drills were used only to verify results obtained from natural radioactivity logs of the open holes. Coring with the shot-hole drills soon became perfected, and the core drills could no longer economically compete.

During 1955, most of the radioactivity logs were made with hand-operated equipment. The U.S. Atomic Energy Commission made a valiant effort to log all the holes for which it had requests with its truck-mounted scintillation equipment, but the volume of work soon surpassed the capacity of the equipment.

Kerr—McGee Oil Industries and Phillips Petroleum Company contracted with Century Geophysical Company to make recorded logs of all their drill holes. Electric logs, resistivity, and self-potential logs, soon were a part of the service, since it was found that cuttings from holes drilled with water left something to be desired when they were to be used for detailed lithologic studies. The information obtainable has proved most valuable in compiling subsurface geologic maps and, more recently, in mine planning.

The problems encountered in learning to correctly interpret radioactivity logs were manifold. Among them was the method of establishing the interpretation curves. Correlations were made by logging cored holes and constructing curves from these comparisons. When the curves were checked from property to property, they did not always compare well. At the time, it was thought that uranium in the various deposits may have reached different equilibrium ratios. It now appears that the grade of the ore body being sampled was a more important factor. If all the samples used in constructing a curve contained more than 0.40 percent $U_3O_8$, the resulting curve was flatter; that is, a given grade was represented by fewer counts per minute than if the samples were taken form the entire grade range 0.10 to 1.00 percent $U_3O_8$,or concentrated in the 0.15 to o.35 percent $U_3O_8$ range. In practice, curves made from this latter group seem to provide the best correlation when the estimated grades are compared with mined grades.

The opening of the mines brought new problems for the geologist. Ore outlines made from exploration and development drilling were based on drill holes spaced from 75 to Zoo feet apart that were rarely surveyed for drift. Development work in the early mines quickly established the need for the drift surveys when the bottoms of drill holes were found as much as 150 feet from the collar location.

It was soon found that ore outlines drawn from such widely spaced drill holes were much too general for proper planning of underground development. Ore sometimes went between weakly mineralized or barren drill holes, and sometimes did not extend from one ore hole to the next. All these factors were responsible for the introduction of long-hole drilling from the underground workings. This drilling is generally done at regular intervals along the advancing sublevel development drifts. Results of the drilling give better definition of known ore, and verify or discount suspected areas of favorability that come to light as the mines develop.

Many of the current ideas concerning the origin of the uranium and reasons for its localization in the Ambrosia Lake area will be found in succeeding papers.

## DAKOTA SANDSTONE DEPOSITS

During the years 1951 to 1953, various prospectors discovered what have proved to be small uranium deposits in the Dakota Sandstone. The most prevalent of these was along the Gallup hogback at the extreme western end of the district. The Hogback No. 4 deposit occurred in a carbonaceous shale near the base of the Dakota and was the only exploited deposit of its kind in the district.

The Silver Spur mine north of Haystack Butte was one of the earliest uranium producers in the district. This deposit was also one of the first in which a relationship between the uranium minerals and fractures was apparent.

## CONCLUSION

Many old and some new geologic problems have been encountered in developing the Grants uranium region. Problems concerning origin of the uranium and reasons for localization of the deposits within the district are still largely unsolved. Problems related to individual deposits have fared considerably better.

Exploration geologists will most certainly find ways to utilize elsewhere some of the special geologic tools and techniques used in developing the Grants uranium region.

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# *Regional and Local Stratigraphy of Uranium-Bearing Rocks*

LOWELL S. HILPERT

## INTRODUCTION

The Grants uranium region encompasses the two most productive sedimentary uranium mining districts in the state, Ambrosia Lake in the west, and Laguna in the east. U.S. Highway 66 extends northwesterly through the southern part of the area and the principal towns, Grants and Laguna, are on the highway in the western and eastern parts, respectively.

This paper presents the regional stratigraphy of the uranium-bearing rocks in the Grants region and the stratigraphic relations between the Grants and Laguna districts.

## GEOLOGIC SETTING

The Grants uranium belt is flanked on the north-northeast by the San Juan Basin, on the east by the Rio Grande trough, and on the south and west by the Acoma sag and the Zuni uplift (Kelley, this memoir, fig. 1; Laverty et al., this memoir, fig. i ). The sedimentary rocks exposed in the area range in age from Pennsylvanian to Cretaceous and rest on the Precambrian core of the Zuni uplift. Associated intrusive and extrusive rocks of the Mount Taylor and Zuni volcanic fields are of Tertiary and Quaternary ages. Regional dip of the sedimentary rocks is generally northward toward the San Juan Basin, but it arcs from northeastward in the Grants district to northwestward in the Laguna district. This regional attitude is modified locally by normal faults and minor folds.

## STRATIGRAPHY

Of the sedimentary rocks that are exposed in the area, mineable uranium deposits are found only in those of Jurassic and Cretaceous ages. These rocks are, in ascending order, the Entrada Sandstone, Todilto Limestone, Summerville Formation, and Bluff Sandstone of the San Rafael Group, and the Morrison Formation, all of Late Jurassic age; and the Dakota Sandstone, of Early and Late Cretaceous age (table ). This sequence is about I000 to 1500 feet thick and rests on either the Wingate Sandstone of the Glen Canyon Group or on the Chinle Formation, both of Late Triassic age. The Morrison Formation and Todilto Limestone are described and discussed in greater detail because they have yielded nearly all the ore and probably contain more than 95 percent of the reserves.

## ENTRADA SANDSTONE

### NOMENCLATURE AND REGIONAL RELATIONS

The Entrada Sandstone is the lowermost uranium-bearing unit and the basal formation of the San Rafael Group in the Grants region. The formation was named from exposures in the northern end of the San Rafael Swell, Utah (Gilluly and Reeside, 1928). Later it was found to extend into northwestern New Mexico (Baker, Dane, and Reeside, 1936, p. 7-8, fig. I2) and, subsequently, was recognized by the U.S. Geological Survey throughout most of the San Juan Basin area when it was supposed that the upper part of the thick cliff-forming sandstone north of Fort Wingate, called the Wingate Sandstone by Dutton (1885), could be correlated with the type section of the Entrada and with widespread exposures of the unit in Utah, Colorado, and northern New Mexico (Baker, Dane, and Reeside, 1947). The name *Entrada Sandstone* was therefore extended by the Survey to include the upper thick sandstone at the type locality of the Wingate Sandstone and the name *Wingate* was shifted to the sandstone below a medial silty unit, with the edict that the original type locality of the Wingate be abandoned (Baker, Dane, and Reeside, 1947, p. 1667-1668).

The silty unit at the base of the Entrada was formerly considered correlative with the Carmel Formation, the lowermost formation of the San Rafael Group (Baker, Dane, and Reeside, 1947). Later work, however, indicated that the Carmel probably extends eastward from Arizona and Utah only to the proximity of New Mexico (Wright and Dickey, 1958, p. 174-175). The silty unit at Fort Wingate is accordingly thought to be correlative with the medial silty member of the Entrada in northeastern Arizona (Strobell, 1956; Harshbarger, Repenning, and Irwin, 1957, p. 35).

The Entrada is the most extensive unit of the San Rafael Group. From a feather edge in central Colorado, it thickens westward to a maximum thickness of nearly 2,000 feet in central Utah and extends southward into northeastern Arizona, northwestern New Mexico, and northward into southwestern Wyoming. It is concordant on the Carmel in eastern Utah and northeastern Arizona and to the east beyond the limit of the Carmel is unconformable on older rocks (Wright and Dickey, p. 172-[1]77).

The Entrada on the Colorado Plateau generally includes two distinct lithologic types. The first is a reddish orange to light gray, well-sorted, quartz sandstone that is conspicuous by sweeping large-scale cross-strata. It forms the entire thickness in most of Colorado but, to the west, interfingers with the second lithologic type, a red, earthy siltstone, which in turn forms the entire thickness of the formation near the western edge of the San Rafael Swell (Wright and Dickey). This siltstone is poorly sorted and weathers into grotesque erosion forms locally referred to as *hoodoos.*

In northeastern Arizona, adjacent parts of Utah, and northwestern New Mexico, Harshbarger, Repenning, and Irwin (p. 35-38) recognized three members—a lower sandy member that is present only in Arizona and Utah, a medial silty member, and an upper sandy member. The medial silty member and upper sandy member, as established at Fort Wingate, have been extended eastward into the Laguna district (Harshbarger, Repenning, and Irwin; Smith, 1954; Rapaport, Hadfield, and Olson, 1952) and generally extend northeastward from Laguna into north-central New Mexico (D. D. Dickey, written communication, 1963).

In most places, the Entrada rests on the Upper Triassic Wingate Sandstone (Harshbarger, Repenning, and Irwin, p. 8, I 1), but at least in the southeastern part of the Laguna district (where the Wingate undoubtedly is missing), it rests on the Chinle Formation (Kelley and Wood, 1946; Silver, 1948; Rapaport, Hadfield, and Olson; Harshbarger, Repenning, and Irwin). Elsewhere in the Laguna district, rocks previously called Wingate might belong in the Entrada. If so, the Entrada rests on the Chinle throughout the district. This problem is discussed below under local relations.

The Entrada Sandstone probably comprises marine, fresh-water, and eolian deposits. In central Utah where it grades into the Carmel Formation it probably represents marine deposits, although fossil evidence is lacking. Eastward, these beds appear to grade into fluvial, lacustrine, and eolian deposits. In the southeastern part of the area, including northwestern New Mexico, the silty member of the Entrada probably largely represents fresh-water and **possibly some marine**

Table 1. *Sequence of stratigraphic units containing uranium deposits in the Ambrosia Lake-Laguna area, New Mexico.*

| System | Age | Formation | Thickness (feet) | Character and distribution | Uranium deposits |
|---|---|---|---|---|---|
| Cretaceous | Early and Late Cretaceous | Dakota Sandstone | <5-125 | Tan to gray, medium-grained quartz sandstone, some interbedded carbonaceous shale and local coal lenses. Local conglomerate-filled scours at base as much as 25 feet deep. | Scattered small deposits, generally near base and closely related to carbonaceous material. A few in Ambrosia Lake district have yielded ore. |
| | | Unconformity | | | |
| Jurassic | Late Jurassic | Morrison Formation | 0-600 | Brushy Basin Member: mostly greenish-gray mudstone and local thick arkosic sandstone units. Contains Poison Canyon sandstone of economic usage near base in Ambrosia Lake district and Jackpile sandstone of economic usage at top in Laguna district. Member is 20-300 feet thick and generally thickens eastward and northward from Ambrosia Lake district. | Sandstone lenses contain many deposits. Very large deposits occur in Jackpile sandstone in Laguna district and large ones occur in Poison Canyon sandstone and other sandstone units in Ambrosia Lake district. |
| | | | | Westwater Canyon Member: light-brown to gray, poorly sorted, arkosic sandstone and some interbedded gray mudstone. Intertongues with Brushy Basin Member and thins from maximum of about 300 feet in Ambrosia Lake district to less than 50 feet in the Laguna district where locally absent. | Contains many large deposits in Ambrosia Lake district. |
| | | | | Recapture Member: distinctive alternating beds of gray sandstone and grayish-red siltstone or mudstone. Beds are a foot to several feet thick. Contact with Bluff Sandstone generally sharp, but intertongues with Westwater Canyon Member. Recapture is less than 50 to more than 200 feet thick. | Contains a few small deposits. One in Laguna district has yielded ore. |
| | | Bluff Sandstone | 150-400 | Pale-red to pale-brown, fine- to medium-grained sandstone. Forms massive cliffs. Upper part marked by thick sets of large-scale crossbeds; lower part grades down into smaller-scale sets of crossbeds and some flat beds. | Contains no deposits. |
| | | Summerville Formation | 90-200 | Alternate beds of pale-brown, thin-bedded sandstone and reddish-brown mudstone or siltstone. Sandstone beds thicken in upper part and grade into overlying Bluff Sandstone; at base grades and intertongues with Todilto. | Contains scattered deposits at base, generally where underlying Todilto Limestone is mineralized. |
| | | Todilto Limestone | 0- 85 | Consists of upper gypsum-anhydrite member, exposed only in Laguna district, 0-75 feet thick; and lower limestone member, gray, laminated in lower part and more massive, contains interbedded siltstone in upper part, 5-35 feet thick. | Contains (mostly in Ambrosia Lake district) many small and some fairly large deposits in the limestone member. |
| | | Entrada Sandstone | 150-250 | Consists of upper unit, 80-250 feet thick, of reddish-orange, fine-grained sandstone with thick sets of large-scale crossbeds and a medial unit, 10-85 feet thick, of red and gray siltstone. In the Laguna district, a lower sandstone unit, 0-30 feet thick, may belong in the Entrada or may be the Wingate Sandstone. Medial unit probably unconformable on Wingate Sandstone in Ambrosia Lake district; lower sandstone unit unconformable on Chinle Formation in Laguna district. | Contains scattered small deposits at top of formation, generally where overlying Todilto Limestone is mineralized. Some have yielded ore. |
| | | Unconformity | | | |
| Triassic | Late Triassic | Wingate Sandstone and Chinle Formation | | Not described. | |

deposits, and the sandy members probably largely represent eolian and some fluvial beds. These features are discussed by Gilluly and Reeside, Baker, Dane, and Reeside (1936), Imlay (1952), Harshbarger, Repenning, and Irwin, and Wright and Dickey.

The Entrada is assigned to the Late Jurassic because of its gradational relations with the Carmel Formation and its stratigraphic position below the Curtis Formation, both of which contain Late Jurassic marine fossils (Gilluly and Reeside, p. 76-79; Baker, Dane, and Reeside, 1936, p. 7-8; Imlay, p. 962).

## LOCAL RELATIONS

In the Ambrosia Lake area, the Entrada crops out north of U.S. Highway 66 and, south of Grants, it is partly exposed in several places along State Highway 117 to a point about 20 miles south of U.S. Highway 66. Approximately from Grants to Laguna, a distance of about 3o miles, the Entrada is covered. In the southern and eastern parts of the Laguna district, the Entrada is well exposed along U.S. Highway 66. The southernmost exposure is about 25 miles south of Laguna.

In the Grants region, the medial silty member is about 10 to 85 feet thick and consists of thin-bedded, red and gray, friable siltstone and fine-grained quartzose sandstone. It grades and interfingers into the upper sandy member, which is 8o to 25o feet thick. The upper sandy member is a reddish orange to light gray, moderately well-cemented and well-sorted, fine- to medium-grained quartz sandstone. It tends to crop out in a prominent rounded cliff or "slick rim," the upper part of which is generally bleached to light gray. The upper sandy member is marked by thick sets of large-scale, planar cross beds, but contains less conspicuous, relatively thin, flat-bedded sets.

Locally in the Laguna district, a sandstone unit lithologically and structurally similar to the upper sandy member of the Entrada occurs at the base of the silty member. According to Silver, this sandstone is the Wingate. Silver, who apparently accepted Dutton's type section at Fort Wingate and referred all the beds between the Chinle and Todilto to the Wingate, indicated in a footnote (p. 74) that his units are equivalent to the revised nomenclature of Baker, Dane, and Reeside (1947). Thus, as shown in Table 2, Silver's lower cliff-forming member is the Wingate Sandstone of Baker, Dane, and Reeside (1947) and Harshbarger, Repenning, and Irwin; Silver's middle slope-forming member is equivalent to the Carmel of Baker, Dane, and Reeside (1947) and to the medial silty member of the Entrada of Harshbarger, Repenning, and Irwin; and Silver's cliff-forming member is equivalent to the Entrada of Baker, Dane, and Reeside (1947) and to the upper sandy member of the Entrada of Harshbarger, Repenning, and Irwin. R. H. Moench, however, who has mapped the Laguna district in detail, includes all of Silver's original Wingate in the Entrada, principally for lack of evidence of erosion under Silver's middle slope-forming member and for the lithologic and structural similarity to the lower and upper cliff-forming members of Silver (R. H. Moench, written communication, 1963).

The lower sandstone unit of Moench unconformably overlies the Chinle Formation on Petoch Butte, in the southwest corner of the Laguna district, and is exposed in a line of outcrops that extends eastward about four miles from the western margin of the district. To the east, the middle siltstone unit of Moench rests on the Chinle, small discontinuous lenses of the lower sandstone unit being exposed only locally. The lower sandstone unit thins from about 3o feet thick at Petoch Butte to a knife edge about six miles to the northeast, and it tends to coarsen southward and downward. Deep scours at the base contain coarse-grained sandstone and locally quartz-pebble conglomerate, and the contact with the overlying siltstone unit is flat and sharp (R. H. Moench, written communication, 1963). Correlation of the Entrada Sandstone units in the Laguna district with the units in the Ambrosia Lake area requires some understanding of the stratigraphic relations of the Wingate Sandstone, which are reviewed briefly.

The Wingate Sandstone is about 35o feet thick at Fort

Table 2. *Nomenclature of the Entrada Sandstone along the south side of the San Juan Basin.*

| Harshbarger, Repenning, and Irwin, 1957 (Fort Wingate area) | | Baker, Dane, and Reeside, 1947 (Fort Wingate) Rapaport, Hadfield, and Olson, 1952 (South side San Juan Basin) | C. T. Smith, 1954 (Thoreau quadrangle) | | Caswell Silver, 1948 (Jurassic overlap, west-central New Mexico) | | R. H. Moench, written communication, 1963 (Laguna district) | |
|---|---|---|---|---|---|---|---|---|
| Entrada sandstone | Upper sandy member | Entrada sandstone | Entrada sandstone | Upper member | Wingate sandstone | Upper cliff-forming member | Entrada Sandstone | Upper sandstone unit |
| | Medial silty member | Carmel formation | | Lower member | | Middle slope-forming member | | Middle siltstone unit |
| Wingate sandstone | | Wingate sandstone | Wingate(?) formation | | | Lower cliff-forming member | | Lower sandstone unit |

Wingate. It thins eastward to less than 100 feet in thickness in the Thoreau quadrangle (Harshbarger, Repenning, and Irwin, p. 11; Smith, 1954) and to about 5o feet north of Grants. In this general area, the Wingate rests on the Chinle Formation and is overlain by the Entrada Sandstone. Both contacts are erosional surfaces but without marked angularity between the beds on either side (Harshbarger, Repenning, and Irwin, p. 11; Smith, 1954; Rapaport, Hadfield, and Olson). The upper contact with the Entrada Sandstone, although not markedly angular, must represent a fairly large time interval because of the respective Late Triassic and Late Jurassic ages of the Wingate and Entrada Sandstones. During this time, some beds at the top of the Wingate probably were removed by erosion prior to deposition of the Entrada. The eastward thinning of the Wingate between Fort Wingate and the Grants area could, therefore, be at least partly a result of such erosion. Correlation of the Wingate and Entrada units in the Ambrosia Lake area with their respective units in the Laguna district is, therefore, dependent partly on the recognition of this erosion surface in the Laguna district.

From the available data, there appear to be two alternative interpretations or correlations. The first interpretation is that the Wingate Sandstone is cut out completely between Ambrosia Lake and Laguna under the erosion surface at the base of the Entrada Sandstone, as shown in Figure 1. If so, the erosion surface on the Wingate in the Ambrosia Lake area is correlative with the erosion surface on the Chinle Formation in the Laguna district. If so, the lower sandstone unit of the Entrada Sandstone of Moench probably grades westward into his middle siltstone unit, which is the correlative of the medial silty member of Harshbarger, Repenning, and Irwin, as shown in Table 2.

The second interpretation is that the erosion surface on the Wingate in the Ambrosia Lake area is correlative with the top of the lower sandstone unit of the Entrada Sandstone of Moench (fig. ). If so, the lower sandstone unit of Moench is correlative with the Wingate Sandstone of Harshbarger, Repenning, and Irwin, as shown in Table 2. This interpretation requires the acceptance of the lack of erosional features and the conformity of the beds along the contact between the lower sandstone and middle siltstone units of Moench as a somewhat abnormal local condition. A completely acceptable correlation of the Entrada units between the two districts will probably require more complete information.

The Entrada Sandstone contains many uranium deposits in the Ambrosia Lake—Laguna area, but few have yielded ore.

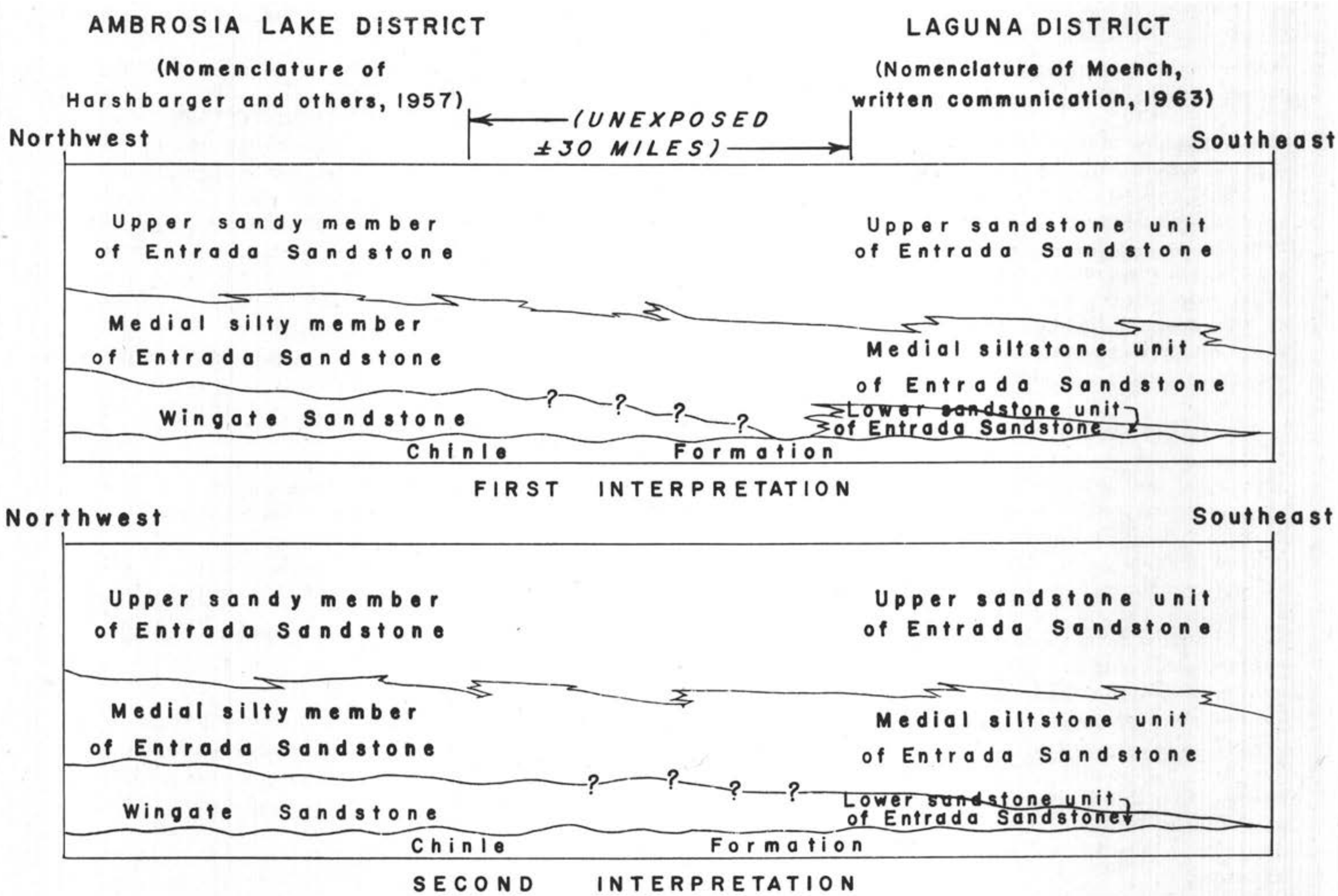


Figure 1

Two interpretive correlations of stratigraphic units of the Entrada Sandstone and the Wingate Sandstone between the Ambrosia Lake and Laguna districts

Most, if not all, the deposits are at the top of the formation and generally represent the basal parts of deposits in the overlying Todilto Limestone. Examples of deposits that have yielded ore are the Sandy, in the Laguna district, and the Zia, in the Grants district.

## TODILTO LIMESTONE

### NOMENCLATURE AND REGIONAL RELATIONS

The Todilto Limestone, which overlies the Entrada Sandstone in the Grants region, was originally described from a ,10-foot-thick exposure of limestone in Todilto Park, New Mexico (Gregory, 1917, p. 55). Baker et al. (1927, p. 8o3) assigned it as a formation in southeastern Utah, but doubted the equivalence of the beds to the Todilto of eastern Arizona and northwestern New Mexico. The Todilto was assigned as a member and "somewhat incongruous associate" of the Morrison Formation (Baker, Dane, and Reeside, 1936, p. 9) and, still later, was included in the San Rafael Group as a member of the Wanakah Formation of southwestern Colorado (Baker, Dane, and Reeside, 1947, p. 1668). Then, because of its distinctive lithology and wide extent, Northrop (1950, p. 36) and Wright and Becker (1951) raised it to formation rank and included it in the San Rafael Group—a status which has been generally accepted (Smith, 1954, p. 13-14; Harshbarger, Repenning, and Irwin, p. 38-39; Anderson and Kirkland, 196o).

The Todilto Limestone is conformable on and generally gradational with the Entrada Sandstone and is distributed throughout most of northwestern New Mexico, adjacent parts of northeastern Arizona, northeastern New Mexico, and southwestern Colorado (Anderson and Kirkland, p. 44). In the San Juan Mountains, Colorado, its equivalent is referred to as the Pony Express Member of the Wanakah Formation (Read et al., 1949; Imlay, p. 96o).

The southern depositional margin of the Todilto is a line o to 20 miles south of U.S. Highway 66 that trends westerly to a point south of Grants and then swings northwesterly and into Arizona west of Todilto Park (Rapaport, Hadfield, and Olson).

The Todilto is composed of two members, a basal limestone member, which is from o to about 40 feet thick and rather widespread, and an upper gypsum-anhydrite member that is more restricted and up to about 125 feet thick. The basal member consists of thin-bedded and laminated, gray, fine-grained limestone, some thin interbeds of siltstone, and near the top some thin seams of gypsum. In some places, the beds are nearly black, and fine-grained black carbonized material is concentrated along the bedding planes. When pulverized, the limestone emits a fetid odor. This characteristic, coupled with the dark hue, has led many to describe the limestone as "petroliferous." Whether or not the limestone contains hydrocarbons and is petroliferous, its content of organic carbon is low. In 14 bulk samples selected by the writer along the outcrop and from drill holes around the San Juan Basin, the content of organic carbon ranged from 0.20 to 1.6 percent and averaged o.6 percent (analyses by Irving Frost, U.S. Geological Survey).

The bedding of the limestone member is contorted in many places. Where strongly disturbed, the beds are folded into a variety of shapes that range from open and closed anticlines to fan folds, recumbent folds, and chevron folds, most of which are asymmetric. Although the folds are fractured and cut by subsidiary faults of small displacement, plastic deformation is dominant. The amplitude of the structures is about equal to their breadth, which ranges from a fraction of an inch to several tens of feet. They generally occur in clusters, and the axes of the individual folds show a crude alignment (Hilpert and Moench, 196o, p. 439, fig. 6). Most folds are confined to the limestone member, but some of the larger ones involve beds in the top few feet of the underlying Entrada Sandstone and basal beds of the overlying Summerville Formation where the upper gypsum-anhydrite member is missing. None of the folds is visibly truncated by bedding planes, but instead die out upward into undisturbed bedding. As the folds are almost entirely restricted to the Todilto, they are considered to be intraformational.\

The gypsum-anhydrite member, which is conformable and gradational with the underlying limestone member, generally occupies the central area of Todilto deposition (Anderson and Kirkland, p. 44). It crops out north of U.S. Highway 66 in the Laguna district and along the eastern side of the San Juan Basin, but its extent to the north and west of these outcrops is only known approximately.

The Todilto is generally considered an evaporite, but the environment of deposition is uncertain and the evidence for its deposition in a marine embayment or lake basin is controversial.

The marine origin is supported largely because of the presence of fossil fish that are thought to have Marine Affinities, lack of chlorines in the abundant surface evidence of a marine connection between the area of Todilto deposition and the Curtis sea. Evidence for a marine connection is found in northeastern Arizona where the upper sandy member of the Entrada is missing and the formation is abnormally thin (Baker, Dane, and Reeside, 1947, p. 1668; Imlay, p. 96o; Harshbarger, Repenning, and Irwin, p. 46-58).

The nonmarine origin is supported largely by the scarcity of fossils, the presence of a nonmarine ostracode (Swain, 1946), and the general gradational contact with the underlying eolian and fluvial sands of the Entrada Sandstone. Recently Anderson and Kirkland (p. 43-45) have questioned the marine affinities of the fish but found no conclusive proof either for a marine origin or for a nonmarine origin. The writer concludes, from the available information, that the Todilto probably was deposited in a shallow semiclosed basin under mixed marine and continental Conditions.

The Todilto Limestone is considered to be Upper Jurassic because of its correlation with the Curtis Formation (Baker, Dane, and Reeside, 1947, p. 1668; Imlay, p. 96o; Gilluly and Reeside, p. 79).

### LOCAL RELATIONS

In the Grants district, only the limestone member of the Todilto crops out, but the gypsum-anhydrite member has been penetrated by drill holes about eight miles north of the outcrop (J. C. Wright, written comunication, 1957). In this district, the limestone member range in thickness from about 5 to 3o feet, averages about 15f t, and comprises three units which are referred to locally as the basal "platy," medial "crinkly," and upper "massive" zones.

The lower two zones, or units, are about equal in thickness and constitute about half the total hickness of the member. The "platy" and "crinkly" units consist of fine-grained, laminated, and thin-bedded limestone with thin siltstone partings and local seams of gypsum. Black dense films of carbonized material are conspicuous locally along the partings in the "crinkly" unit. The bedding in the "platy" unit generally is undisturbed, but in the "crinkly" unit it is intensely crenulated. The "massive" unit consists of more coarsely crystalline limestone with indistinct bedding and varies in thickness from place to place. In many places it contains breccia of limestone cemented by calcite, and locally the top of the unit is a breccia with fragments of limestone embedded in sand derived from the overlying Summerville Formation. The upper part of the "massive" unit also contains lenses of siltstone, indicating a gradational contact with the overlying Summerville.

In the Laguna district both the limestone and gypsum-anhydrite members are exposed. The limestone member crops out along both sides of U.S. Highway 66 and is as much as 35 feet thick in the vicinity of the Sandy mine, but to the north, where it is overlain by the gypsum-anhydrite member, it averages only about ten feet thick. It consists of two units of about equal thickness, a lower bedded unit and an upper massive unit that are lithologically and structurally similar to the "platy" and "massive" zones or units in the Ambrosia Lake area. The lower, or bedded unit, ranges in thickness from a few feet to as much as 35 feet and probably averages about ten feet. The "massive" unit is discontinuous and highly variable in thickness, being locally as much as 15 feet thick.

According to R. H. Moench (written communication, 1963), where the overlying gypsum-anhydrite member is missing, the massive limestone unit and basal sandstone beds of the Summerville Formation in many places are intimately mixed and thin layers of sandstone and siltstone are tightly folded. These relations, when considered with the general gradational nature of the Todilto—Summerville contact, suggest flowage after deposition and before consolidation of the sediments (R. H. Moench, written communication, 1963). The brecciation and mixing in the same straigraphic position in the Ambrosia Lake area, as mentioned above, suggest the same kind of flowage.

The gypsum-anhydrite member is exposed in the Laguna district mostly north of U.S. Highway 66 where it ranges in thickness from o to 75 feet and forms conspicuous knolls or hummocks on benches of the limestone member. This exposure is the southern end of the thick part of the member, the axis of which trends north along the east side of the San Juan Basin. At the surface, the member is almost entirely gypsum, but the hummocks in many places are capped by a thin bed of limestone (R. H. Moench, written communication, 1963). In a drill hole at the Jackpile mine, the unit is about 75 feet thick and almost entirely anhydrite. A little gypsum is present at the top, and the lower half shows irregular limestone laminae (R. H. Moench, written communication, 1963).

Many uranium deposits occur in the Todilto Limestone. All are in the limestone member and most are near the base, but some are in the middle or top or occupy the entire limestone interval. Many are not confined entirely to the limestone but extend into the underlying Entrada Sandstone or into the overlying Summerville Formation. Most of the deposits are in the Grants district but some occur in the Laguna district, as well as elsewhere in northwestern New Mexico. All the deposits are closely related to the intraformational folds in the limestone member. These folds, which are probably Late Jurassic in age, are best developed and concentrated along the southern margin of the San Juan Basin (Hilpert and Moench).

## SU MMERVILLE FORMATION

### NOMENCLATURE AND REGIONAL RELATIONS

The Summerville Formation was named from exposures in the northern end of the San Rafael Swell, Utah (Gilluly and Reeside, p. 8o). Baker, Dane, and Reeside (1936, p. 32) extended the nomenclature to western Colorado and to the vicinity of the Four Corners. Later, Harshbarger, Repenning, and Jackson (1951, p. 4o, 97, pl. z) extended it to Fort Wingate. The terminology then was extended eastward from Fort Wingate to Laguna (Rapaport, Hadfield, and Olson, p. 27-29). For exposures in the area north of Thoreau, Smith (1954, p. [1]415), used the name *Thoreau Formation* and correlated the lower even-bedded member of this unit with the Summerville. Freeman and Hilpert (1956, p. 316, 318) used the terminology of Rapaport, Hadfield, and Olson (1952) and extended it northward to Cuchillo Arroyo on the eastern side of the San Juan Basin.

Regionally, the Summerville generally consists of a lower silty member and an upper sandy member ranging from about 5o to 33o feet in total thickness. The silty member conformably overlies the Curtis Formation in the San Rafael Swell (Gilluly and Reeside, p. 8o). Southeastward from the Swell, it progressively overlies the Entrada Sandstone and Todilto Limestone (Baker, Dane, and Reeside, 1947, p. 32; Strobell; Harshbarger, Repenning, and Irwin, 1957, pl. 3). The lower silty member is a sequence of soft reddish brown mudstone and thin-bedded, silty sandstone beds that locally are gypsiferous and that in many places exhibit subaqueous slump structures (Harshbarger, Repenning, and Irwin, 1957, p. 41; Strobell). It grades upward into the upper sandy member which consists mostly of reddish brown and pale brown, fine-grained, even-bedded sandstone and some interbedded siltstone. The sandstone beds progressively thicken toward the top at the expense of the interbedded siltstone and, in the southeastern part of the area, the sandstone beds at the top individually are as much as several feet thick.

In general, the Summerville thickens northwestward and the grain size coarsens from Utah eastward and southeastward. The Summerville passes laterally into the Curtis Formation and is in part a marginal facies of the Curtis in east-central and southwestern Utah (Baker, Dane, and Reeside, 1936, p. 47). It grades into the Cow Springs Sandstone in northeastern Arizona and west-central New Mexico (Harshbarger, Repenning, and Irwin, pl. 3), and occupies the stratigraphic position of the elastic beds above the Pony Express Member of the Wanakah Formation in parts of southwestern Colorado (Read et al.).

The Summerville Formation is generally considered to represent deposits laid down in relatively quiet and shallow marine waters, but the presence of mud cracks, ripple marks, and some g sum Gilluly 'and Reeside, p. 80) poor sorting (especially in tHe southeast), and the lack of fossils probably indicate some subaerial deposition. Most likely the two members of the Summerville represent transgressive and regressive phases of a Curtis and Summerville sea, the lower silty member being roughly contemporaneous with the Curtis deposition, and the upper sandy member being representative of the regressive phase (Harshbarger, Repenning, and Irwin, p. 42).

### LOCAL RELATIONS

In the Grants and Laguna districts, the Summerville is about 90 to 200 feet thick and is exposed in many places. It generally crops out on stripped-back benches of the Todilto Limestone as a talus-covered slope and an overlying horizontally ribbed cliff at the base of the massive cliff of Bluff Sandstone. The contacts of the Summerville are gradational and arbitrary. Freeman and Hilpert selected the base as the top of the uppermost limestone bed of the Todilto and selected the top as the top of the uppermost persistent siltstone-mudstone bed. This interpretation generally agrees with that presented by Rapaport, Hadfield, and Olson and has been followed by R. H. Moench (written communication, 1963) and E. S. Santos (oral communication, 1963).

In 'the Grants district, the Summerville is partly exposed in many places and completely exposed in a few places north of U.S. Highway 66 and east of State Highway 117. At Haystack Butte, about six miles north of Bluewater, it is about 160 feet thick (T. E. Mullens and L. C. Craig, written communication, 1950) and, at Red Bluff, about ten miles north of Grants, it is about 215 feet thick. At this section, a 5-foot-thick unit was measured by V. L. Freeman and the writer above a basal covered unit which was estimated to be about 80 feet thick. About 20 miles south of Grants on State Highway 117, a 15-foot-thick quartzite-pebble conglomerate is exposed at the base of the Summerville and rests on the Entrada Sandstone. The conglomerate contains fairly well rounded pebbles, some as much as three inches in diameter, imbedded in poorly sorted sand and silt.

In the Laguna district, the Summerville Formation was described by R. H. Moench (written communication, 1963) as

. . the lower silty facies of Harshbarger and others (1957 p. 39) and the buff shale member of Kelley and Wood (1946) and Silver (1948, p. 77) . . .", which conforms with the usage of Rapaport, Hadfield, and Olson, and of Freeman and Hilpert (p. 312).

The Summerville is exposed in the district in a line of cliffs along the southern part of Mesa Gigante and in many buttes and mesas south of U.S. Highway 66. It ranges in thickness from about 1 00 to 180 feet. According to Silver (p. 78), it thins and coarsens southward. At Petoch Butte, it is about 140 feet thick and about 17 miles south of Petoch Butte is cut out under a pre-Dakota erosion surface. At its southern margin, the Summerville contains a basal pebble conglomerate (Silver, p. 78) which may be equivalent to the conglomerate south of Grants (*see* above). In the northern part of the district, the formation is covered and the nearest exposure north of the district is in Cuchillo Arroyo where a 60-foot-thick section is exposed at the base of the Morrison Formation (L. C. Craig, written communication, 1951; Freeman and Hilpert, p. 316).

In many places in the Laguna and Grants districts, the Summerville beds are intensely contorted, particularly in the lower part, and the formation is cut by numerous sandstone pipes. The pipes extend into the overlying Bluff Sandstone and are considered to be intraformational collapse structures that formed during the accumulation of the highest beds they cut (Hilpert and Moench).

Scattered uranium deposits occur in the Summerville Formation at the base, but few if any are of mineable grade. Most are extensions of deposits that occur in the underlying Todilto Limestone.

## BLUFF SANDSTONE

### NOMENCLATURE AND REGIONAL RELATIONS

The Bluff Sandstone, which conformably overlies the Summerville Formation in the Grants region was described by Gregory (1938, p. 58) from exposures at Bluff, Utah, and assigned as the basal member of the Morrison Formation in southeastern Utah. In southwestern Colorado, Goldman and Spencer (1941, p. 1750) called its equivalent the Junction Creek Sandstone Member of the Morrison, and Eckel (1949, p. 29) later raised the Junction Creek to formation rank. Read et al. redefined it as a member of the Wanakah Formation, a unit that occupies the stratigraphic position of the Summerville Formation in south-central Colorado. Craig et al. (1955, p. 133) accepted the correlation of the Junction Creek with the Bluff by Goldman and Spencer (p. 1759), but considered the Bluff as a separate formation assigned to the San Rafael Group because it tongued and intergraded with the Summerville in southeastern Utah and in bedding and lithology resembled the San Rafael Group (Craig et al., p. 133-134).

From Utah, the Bluff Sandstone extends southward into northeastern Arizona where it tongues with the Salt Wash Member of the Morrison Formation (Craig et al., p. 133) and coalesces with the Cow Springs Sandstone (Harshbarger, Repenning, and Irwin, p. 42).

In the southeastern part of the Grants region, the lithologic member names required by the Survey during wartime inactivity of the names committee were used by Kelley and Wood for the units between the Entrada Sandstone and Dakota(?) Sandstone. These were, in ascending order, the Todilto Gypsum Member, buff shale member, brown-buff sandstone member, white sandstone member, and variegated shale member of the Morrison Formation. Somewhat later, Smith (1951; 1954, p. 15) proposed a partly new set of names for the same stratigraphic interval in the Thoreau quadrangle, just west of the Ambrosia Lake area. Smith's sequence was the Thoreau Formation below, which consisted of a lower and an upper member, and the Morrison Formation above. Prior to this, the Utah terminology of Craig et al. had been followed by Rapaport, Hadfield, and Olson and, subsequently, was used by Freeman and Hilpert for rocks exposed along the southeast side of the San Juan Basin. Thus, in the Grants region, the formations between the Entrada Sandstone and Dakota Sandstone are, in ascending order, Todilto Limestone, Summerville Formation, Bluff Sandstone, and Morrison Formation. As shown in Table 3 the Bluff is the equivalent of the white sandstone and brown-buff sandstone members of the Morrison of Kelley and Wood and the upper member of the Thoreau Formation of Smith (1954)•

From southeastern Utah, where it attains a thickness of about 350 feet, the Bluff Sandstone thins southward and grades into the Cow Springs Sandstone in northeastern Arizona. It is generally less than 1 00 feet thick in Arizona and is about 30 feet thick along the Arizona—New Mexico boundary and near Toadlena, New Mexico. From Toadlena, it grades southward into the Summerville (Harshbarger, Repenning, and Irwin, p. 40, 43). On the south side of the San Juan Basin, the Bluff generally is about 150 to about 400 feet thick and is probably thickest south of Grants and northeast of Laguna. North of the Laguna district the Bluff is absent and may grade into the Summerville and lower part of the. Morrison Formation south of Cuchillo Arroyo (Freeman and Hilpert, p. 316)

Table 3. *Nomenclature of the stratigraphic units between the Entrada and Dakota Sandstones along the south side of the San Juan Basin*

| Modified from Harshbarger, Repenning, and Irwin, 1957 (Fort Wingate) | | C. T. Smith, 1954 (Thoreau quadrangle) | | Freeman and Hilpert, 1956 (Part of northwestern New Mexico) Rapaport, Hadfield, and Olson, 1952 (South side San Juan Basin | | Kelley and Wood, 1946 (Lucero uplift) Caswell Silver, 1948 (Jurassic overlap, west-central New Mexico) | |
|---|---|---|---|---|---|---|---|
| Dakota Sandstone | | Dakota(?) formation | | Dakota sandstone | | Dakota(?) sandstone | |
| Morrison Formation | Brushy Basin Member | Morrison Formation | Brushy Basin shale member | Morrison formation | Brushy Basin member | Morrison formation | Variegated shale member |
| Morrison Formation | Westwater Canyon Member | Morrison Formation | Prewitt sandstone member | Morrison formation | Westwater Canyon member | Morrison formation | Variegated shale member |
| Morrison Formation | Recapture Member (intertongues with Cow Springs Sandstone) | Morrison Formation | Chavez member | Morrison formation | Recapture member | Morrison formation | Variegated shale member |
| Cow Springs Sandstone | | Thoreau formation | Upper member | Bluff sandstone | | Morrison formation | White sandstone member; Brown-buff sandstone member |
| Summerville Formation | | Thoreau formation | Lower member | Summerville formation | | Morrison formation | Buff shale member |
| Todilto Limestone | | Todilto limestone | | Todilto limestone | | Morrison formation | Todilto gypsum member |
| Entrada Sandstone | | Entrada sandstone | | Entrada sandstone | | Wingate sandstone | |

or may thin to a depositional edge. In the southwest part of the San Juan Basin the Bluff coalesces westward with the Cow Springs Sandstone west of Thoreau.

In most places, the Bluff intertongues and is gradational with the Summerville and the contact between the two is rather arbitrary. The contact generally is selected between the uppermost persistent siltstone and overlying thick-bedded sandstone.

The Bluff generally consists of pale red to pale brown, fine- to medium-grained, fairly well-sorted and-cemented quartz sandstone. It crops out as a massive, smooth, rounded cliff above the talus-covered slope ands cribbed cliffs of the Summerville. Bedding of the Bluff is marked by thick sets of large-scale, high-angle, trough-type cross beds, principally in the Upper part. Some thin flat-bedded and cross-bedded sets are present, particularly in the lower part. These beds are mostly small and medium scale.

The Bluff is generally considered a product of both sub-aerial and eolian deposition. The lower part probably indicates some deposition in shallow water and some wind deposition, and the upper part largely wind action. Craig et al. (p. 133) considered the Bluff in Arizona to be a tongue of the Cow Springs Sandstone. Harshbarger, Repenning, and Irwin (p. 42, 44) believed the materials of both to have been derived from dunes that advanced northward from highlands in central Arizona and New Mexico, referred to as the Mogollon Highlands. The dip directions of the cross beds in the Laguna district indicate that the Bluff there was derived from the west and southwest, presumably from the same source area (R. H. Moench, written communication, 1963).

The Bluff Sandstone is generally considered to be Upper Jurassic because of its intertonguing relations with the Summerville Formation.

## LOCAL RELATIONS

In the Grants district the Bluff sandstone is exposed in many places along the outcrop north of U.S. Highway 66. South of Highway 66 it is exposed along the escarpment east of State Highway 117. At Haystack Butte it is about 160 feet thick (T. E. Mullens and L. C. Craig, written communication, 1950) and at the Red Bluff section north of Grants it is about 270 feet thick. According to Thaden and Santos (1957, p. 73), the Bluff thickens southward from Grants, possibly to more than 300 feet.

In the Laguna district the Bluff is well exposed in cliffs on the west and south sides of Mesa Gigante and in numerous buttes and mesas south of U.S. Highway 66. The Bluff averages about 300 feet in thickness, and the thickest exposure, which is about 400 feet, is on the south side of Mesa Gigante; on Petoch Butte, south of Laguna, where the upper part has been removed by pre-Dakota erosion, the Bluff is about 220 feet thick (R. H. Moench, written communication, 1963). Southward from Petoch Butte it is progressively cut out under the pre-Dakota erosion surface and about 25 miles south of Laguna has been entirely removed (Silver).

Moench has found that in the eastern part of the district, the lower part of the Bluff is light reddish brown and the upper part is light yellowish gray, whereas in the western part the entire formation is light yellow gray or very pale orange. He attributes the lighter colors in the lower part of the Bluff in the western part to alteration effects of numerous diabase dikes and sills. Because of this difference, identification of the Bluff across the Laguna district cannot be based solely on color (R. H. Moench, written communication, 1963).

The Bluff Sandstone contains no known uranium deposits.

## MORRISON FORMATION

### NOMENCLATURE AND REGIONAL RELATIONS

Cross (1894, p. 2) applied the name *Morrison Formation* to exposures near Morrison, Colorado; since then, the Morrison has been recognized throughout much of the western interior of the United States, including Colorado, eastern Utah, part of northeastern Arizona, and northwestern New Mexico. The age, stratigraphic relations, and definition of its members, however, have been subjected to much work and discussion, which has led to a voluminous literature. For a general background, the reader is referred to Cross, Emmons, Cross, and Eldridge (1896); Lupton (1914); Gilluly and Reeside; Baker, Dane, and Reeside (1936); Gregory (1938); Stokes (1944); Waldschmidt and LeRoy (1944); Harshbarger, Repenning; and Jackson; Harshbarger, Repenning, and Irwin; and Craig et al.

The Morrison is generally considered to be Late Jurassic (Imlay, p. 953-960), although the upper part in some places might be younger.

Craig et al., in a summary report based on extensive stratigraphic studies in the Colorado Plateau, gave a rather detailed discussion of the stratigraphic relations and over-all distribution. They defined the base of the Morrison in the Colorado Plateau region as the base of the terrestrial, fluvial Jurassic deposits overlying beds of the marine and marginal marine San Rafael Group, and outlined the Morrison as a crude, lenslike mass that extends from a wedge-edge in northeastern Arizona northeastward across Utah, northwestern New Mexico, and western Colorado. Throughout this region, the Morrison is generally conformable on the San Rafael Group, ranges in thickness from 300 to 900 feet and averages about 500 feet.

The Morrison is mostly a sequence of interbedded sandstone, claystone, or mudstone, some thin-bedded limestone, and some conglomerate. The sandstone units range from a foot or so to more than 100 feet in thickness, are arkosic, contain much interstitial clay or mudstone and locally carbonized plant fragments and fossil logs. The sandstone is commonly cross-stratified and has conspicuous cut-and-fill structures in many places. The upper part of the Morrison is mostly claystone or siltstone and some sandstone. The claystone contains much bentonitic material which tends to swell when wet.

The Morrison generally grades from conglomeratic sandstones in the southwestern part of the region to finer material, mostly mudstone, in the northeastern part. It wedges out in northeastern Arizona and west-central New Mexico partly as a result of pre-Dakota erosion (Craig et al.).

Regionally, the Morrison consists of four members which are, in ascending order, the Salt Wash Recapture, Westwater Canyon, and Brushy Basin. Each of the lower three constitutes a fanlike lens that generally grades from conglomeratic sandstone along the southwestern margin to mudstone along the northeastern recognizable limit of the member. The Brushy Basin, the uppermost member, is largely a lenticular unit of claystone (much of it bentonitic), some thin beds of limestone, and some silt and sand (Craig et al., p. 138-156).

Studies of the lithology and sedimentary structures of the Morrison by Craig et al. indicate that the sediments were largely derived from a landmass in west-central Arizona and west-central New Mexico and were deposited by an aggrading system of northeastward-flowing streams. The sediments of the Brushy Basin Member were probably deposited in a mixed lacustrine and fluvial environment in which the fluvial material probably came largely from the Mogollon Highland to the south (Harshbarger, Repenning, and Irwin, p. 55). The bentonitic claystone is interpreted to be a derivative of volcanic ash (Craig et al., p. 160).

All four members of the Morrison are present in northwestern New Mexico, but in the southern part of the. San Juan Basin, the Salt Wash is absent and the other three members have been referred to by different names (Kelley and Wood; Silver; Smith, 1954). Freeman and Hilpert used the terminology of Craig et al., and extended it across the southern side of the San Juan Basin. Others (Granger et al., 1961; Schlee and Moench, 1961; Granger, 1962) have followed the terminology generally. Thus, as shown in Table 3, the Recapture, Westwater Canyon, and Brushy Basin members are the correlatives, respectively, of the Chavez Member, Prewitt Sandstone Member, and the Brushy Basin Shale Member of the Morrison Formation of Smith (1954); they are collectively the equivalent of the variegated shale member of the Morrison Formation of Kelley and Wood and Silver.

### LOCAL RELATIONS

In the Grants district, the Morrison is widely exposed north of U.S. Highway 66 and is partly exposed immediately south of Highway 66 and east of State Highway 117. In the Laguna district, it is exposed in a belt extending northeasterly across the district and is best exposed for several miles north from Laguna. In general, the Morrison rests conformably on the Bluff Sandstone, although locally the surface contains shallow scours. The Dakota Sandstone overlies the Morrison unconformably, but generally without marked angularity. However, in the Grants district, about two miles south of U.S. Highway 66 on State Highway 117, the Morrison is cut out under the pre-Dakota erosion surface and, southward from the vicinity of the Jackpile mine in the Laguna district, the pre-Dakota erosion surface successively truncates older beds; at Petoch Butte the entire Morrison has been removed (Silver). The angular relations of the beds on each side of the unconformity can be observed best immediately southwest of the Jackpile mine where the Dakota Sandstone rests on truncated broad folds in the Morrison.

Throughout most of the Grants region, the Morrison, comprising the Recapture, Westwater Canyon, and Brushy Basin members, is 0 to about 600 feet thick, averaging about 450 feet. In the Grants district, each member has an average thickness of 150 feet, but in the Laguna district the Recapture and

Westwater Canyon members are thinner and somewhat discontinuous and the Brushy Basin is thicker. Also in the Laguna district, a prominent sandstone unit, informally referred to as the Jackpile sandstone of economic usage, is present in the upper part of the Brushy Basin. The stratigraphic relations between these units in the two districts are shown in Figure 2.

The Recapture Member is conformable on the Bluff Sandstone. The contact generally is even and sharp and is marked by changes in lithology, bedding structures, and colors. In places, the two units grade and intertongue, and in some places the Recapture rests on scoured or channeled surfaces that have a foot or so of local relief. The Recapture in the Grants district generally ranges in thickness from about 50 to more than zoo feet and has an average thickness of about 15o feet. In the Laguna district, it is thinner and generally ranges in thickness from about 25 to 5o feet, although locally it is as much as loo feet thick. In Cuchillo Arroyo north of the district, it is about 275 feet thick (Freeman and Hilpert, p. 316, 325).

The Recapture consists mostly of distinctive alternating gra ish red and ra beds of sandstone, siltstone, mudstone, an a ew t in a tone. The beds generally range from a foot or so to several feet thick and some beds of sandstone are as much as ten feet or more thick. The sandstone is soft, clayey, poorly sorted, and mostly fine- to medium-grained. Locally, it contains small lenses of granules and small pebbles and concentrations of carbonized plant debris. It is commonly ripple-laminated and thin-bedded. Cross beds are not conspicuous and where present are small to medium-scale' and planar type.

The Recapture contains a few uranium deposits, but they are generally small and of low grade.

The Westwater Canyon generally overlies the Recapture throughout the area. From place to place, the contact is a scour surface or is gradational or the members intertongue. The Westwater Canyon is thickest in the Ambrosia Lake area where it ranges from less than 5o to nearly 30o feet in thickness and has an average thickness of about 15o feet. In the Laguna district, it ranges in, thickness from about ten to more than 10o feet, but generally has an average thickness of less than 5o feet; it is absent locally on the south end of Mesa Gigante and, in the southwestern part of the district, locally fills scours that cut through the Recapture and into the Bluff Sandstone (R. H. Moench, written communication, 1963). North of the Laguna district at Cuchillo Arroyo, it is about 17o feet thick (Freeman and Hilpert, p. 316, 324).

The Westwater Canyon is mostly a light yellow-brown to gray, fine- to coarse-grained, poorly sorted, cross-bedded sandstone. It is arkosic and contains some small lenses of granules and small pebbles and some thin seams or beds of gray mudstone and siltstone. Grains and granules of pink feldspar and flecks of white kaolin are conspicuous in hand specimens. Fragments of silicified logs are present locally, but most are small. e cross-bedding is generally small- to medium-scale trough type. The cross beds dip southeastward in the lower part and northeastward in the upper part in the Ambrosia Lake area (E. S. Santos, written communication 1963) and generally northeastward in the Laguna district (R. H. Moench, written communication, 1963). Pipelike collapse structures similar to those in the Bluff and Summerville occur in a number of places in the Westwater Canyon Member in the Ambrosia Lake area.

The Westwater Canyon contains many large uranium deposits in the Ambrosia Lake area, in the Smith Lake area north of Thoreau, and northeast of Gallup. These deposits are closely associated with fine-grained carbonaceous matter that coats the sand grains and fills pore spaces within the sandstone.

The Brushy Basin conformably overlies the Westwater Canyon Member and is overlain unconformably by the Dakota Sandstone. The contact with the Westwater Canyon is generally gradational and the two members intertongue extensively; so the selection of the contact is quite arbitrary. The writer defines the contact as the base of the lowermost persistent mudstone or claystone unit. In the Ambrosia Lake—Laguna area, the Brushy Basin is about 20 to more than 300 feet thick. It generally thins westward and is cut out northeast of Gallup under the pre-Dakota unconformity. It thickens eastward from the Grants district into the Laguna district (fig. 2) and, as indicated by drill data, apparently northward as well.

The Brushy Basin in the general area is chiefly greenish gray mudstone but contains much interbedded sandstone and a few thin beds of gray limestone.The sandstone beds are similar in color and litology to the Westwater Canyon, range from a foot or so to several tens of feet in thickness, and some of them extend for several miles. Also, sandstone beds at the to of the Westwater Canyon intertongue with the lower part of the Brushy Basin. One of these in the Ambrosia Lake district extends eastward or northeastward back from the outcrop and is referred to as the Poison Canyon sandstone of economic usage (Hilpert andreeman). Its eastward and northward extent is uncertain. In the Laguna district, a relatively thick and extensive sandstone unit at the top of the Brushy Basin immediately under the Dakota Sandstone is referred to as the Jackpile sandstone of economic usage (Hilpert and Freeman). It is best exposed at the Jackpile mine where it contains the large Jackpile deposit and other nearby deposits. The Jackpile sandstone has been described in some detail by Schlee and Moench, from whose report it will be summarized here.

The Jackpile sandstone is a northeast-trending lens as much as 13 miles wide, more than 33 miles long, and locally zoo feet thick. It broadens northward and divides into two smaller trough-shaped fingers. It is an erosional remnant of the original mass and, before it was beveled by pre-Dakota erosion, may have extended over a much more extensive area. It apparently occupies a pre-Dakota structural depression, as indicated by the angular unconformity at the base of the Dakota, intertonguing of the sandstone at the base of the Jack-pile sandstone with the Brushy Basin mudstone, and the apparent thickening of the part of the Morrison Formation that underlies the Jackpile sandstone toward the center of the sandstone lens.

The Jackpile sandstone is similar to the Westwater Canyon, except for a higher content of kaolin, color differences, and other evidences of slight alteration: It is generally chalky white in the upper part and yellow-gray in the lower part. The white color results partly from the kaolin content and partly from removal of pigmenting colors. The kaolin is an alteration product of feldspar minerals caused by weathering during the interval between deposition of the Morrison and Dakota sediments (Leopold, 1943; Schlee and Moench; Granger). The cross beds in the Jackpile sandstone dip gen-

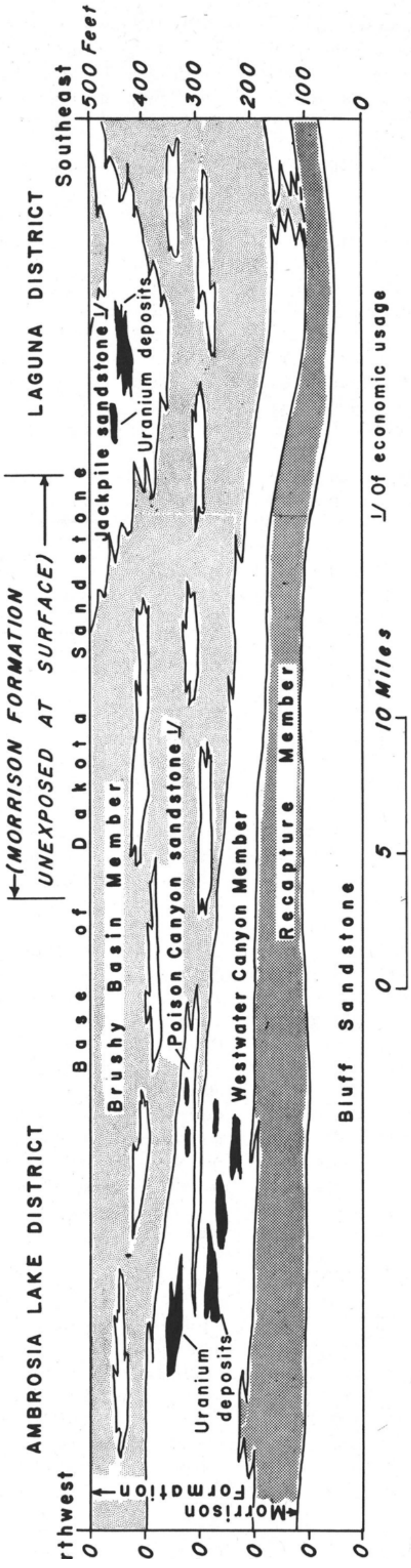


Figure 2

GENERALIZED GEOLOGIC SECTION SHOWING THE STRATIGRAPHIC RELATIONS OF THE MORRISON FORMATION BETWEEN AMBROSIA LAKE AND LAGUNA erally northeastward, indicating a northeastward direction of transport which is parallel to the axis of the sandstone unit.

Other sandstone units in the Brushy Basin occur immediately under the Dakota Sandstone west of the Ambrosia Lake area and north of the Laguna district and show bleaching (probably kaolinized) in the upper part similar to the Jackpile sandstone. One of these units crops out about six miles north of Prewitt and contains the Francis and Evelyn uranium deposits. Another unit crops out on the east side of the San Juan Basin (Swift, 1956).

Most, and by far the largest, of the uranium deposits in the Ambrosia Lake—Laguna area are in the Brushy Basin and Westwater Canyon members of the Morrison Formation.

The Westwater Canyon contains many large deposits such as the Dysart and Cliffside and others to the west. Sandstone lenses in the Brushy Basin also contain many deposits. The largest ones are in the Jackpile sandstone in the Laguna district, including the large Jackpile deposit. Also, the pipelike Woodrow deposit in the Laguna district is in the interval that extends from the lower part of the Jackpile sandstone into the underlying mudstone. In the Ambrosia Lake area, deposits in sandstone lenses in the Brushy Basin are generally smaller than those in the Westwater Canyon.

The Recapture Member contains relatively few deposits; most are not of mineable size and grade; an exception is the Chaves deposit, which has yielded some ore.

# DAKOTA SANDSTONE

## NOMENCLATURE AND REGIONAL RELATIONS

The Dakota Sandstone of Early and Late Cretaceous age unconformably overlies the Morrison Formation and older strata and is overlain conformably by the marine Mancos Shale of Late Cretaceous age throughout the Grants region. The name *Dakota Group* was applied originally by Meek and Hayden (1862) to rocks of Late Cretaceous age near Dakota, Nebraska. Since then the name, or qualifications of it such as Dakota(?) Formation, Dakota(?) Sandstone, and Dakota Sandstone, has been extended over large areas in the western States to rocks in approximately the same stratigraphic position. In northwestern New Mexico, the name has been applied generally to the lowermost strata of Cretaceous age that unconformably rest on the Jurassic and older strata.

In the south part of the San Juan Basin, the Dakota generally is about 75 to 100 feet thick, except in the Laguna district where it is locally less than five feet thick (Dane and Bachman, 1957, p. 96; Young and Ealy, 1956; Dane, 196o, p. ; Smith, 1954, p. 18; R. H. Moench, written communication, 1963). It consists mostly of tan to gray quartz sandstone, dark gray carbonaceous shale, and local lenses of conglomerate and impure coal. The sandstone ranges from fine-to coarse-grained but generally is medium-grained, is clean, and contains numerous small molds of carbonized plant fragments. The sand grains are fairly well rounded and cemented by silica. The Dakota from place to place forms one or more sandstone units, which are generally separated by thin beds of carbonaceous shale and locally by coal lenses. The sandstone units are generally cross-bedded in the lower part and even-bedded in the upper part. Most of the carbonaceous shale is at the base. Conglomerate lenses occur locally and most y at the base of the formation where they occupy scours in the top of the Morrison Formation. Some scours are as much as 25 feet deep and are characteristically filled by a mixture of quartz sand, quartz pebbles, and scattered pieces of fossil plant debris.

The Dakota crops out in most places as prominent benches and in vertical blocky cliffs. The cliff faces are commonly iron-stained and hence readily recognized above the light-colored sandstone and gray mudstone of the Morrison Formation.

The Dakota Sandstone in northwestern New Mexico was assigned a Late Cretaceous age by Cobban and Reeside (1952, chartrob). Fossil data from the basal part of the Dakota near Acoma confirm that it is not older than Late Cretaceous (Dane, 1959, p. 9o). Dane and Bachman (p. 97, 98) indicated that in the Gallup area, however, part of the Dakota may be of Early Cretaceous age.

The Dakota Sandstone is generally considered to be an accumulation of near-shore continental deposits that were laid down by streams and in swamps during and following a long period of erosion and weathering which must have lasted at least throughout most of Early Cretaceous time. The cross-bedded sandstone, conglomerate-filled channels, and inter-bedded carbonaceous shale and coal are indicative of such conditions. Dane and Bachman (p. 97) interpreted the Dakota in the Gallup area as a transgressive deposit that is partly a fluvial, partly a lagoonal, and partly an off-shore sandy marine unit and interpreted the advance of the sea as originating probably from the east and south, and representing the last phase of Dakota deposition. Moench (written communication, 1963) believes similar conditions prevailed in the Laguna district, and he interprets the sands and gravels in the lower part of the Dakota as deposits from streams that probably flowed from the west.

## LOCAL RELATIONS

In the Ambrosia Lake area, the Dakota crops out in low cliffs, on mesa tops, and in prominent benches north of U.S. Highway 66 and east of State Highway 117. In many places, it consists of an upper sandstone unit and a lower, somewhat thinner, carbonaceous shale unit. It generally is about 5o to 125 feet thick and averages about 8o feet thick. In the Laguna district, it likewise crops out in low cliffs, on mesa tops, and in prominent benches throughout the area and ranges from less than 5 feet to more than too feet thick; in the northeastern part of the district, sandstone is absent locally and the formation consists entirely of black shale (R. H. Moench, written communication). The average thickness in the Laguna district is probably less than 5o feet.

A few uranium deposits occur in the Dakota Sandstone, mostly near the base in channel scours, or closely associated with carbonized plant material. A few in the Ambrosia Lake area, such as the Silver Spur, have yielded ore.

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# *Tectonic Setting*

VINCENT C. KELLEY

The Grants uranium belt, as encompassed in this memoir, extends west-northwest in a strip some 15 to 20 miles wide and 95 miles long. It extends from the Rio Grande trough on the east to the Gallup sag on the west. It crosses the northwestern end of the Zuni uplift and follows its northern flank along the arbitrarily defined boundary between the uplift and the Chaco slope, southern flank of the San Juan central basin (fig. i ). Beneath Mount Taylor, the belt crosses the Acoma sag to the Puerco fault-belt margin of the Rio Grande trough.

The principal tectonic elements in which the belt occurs

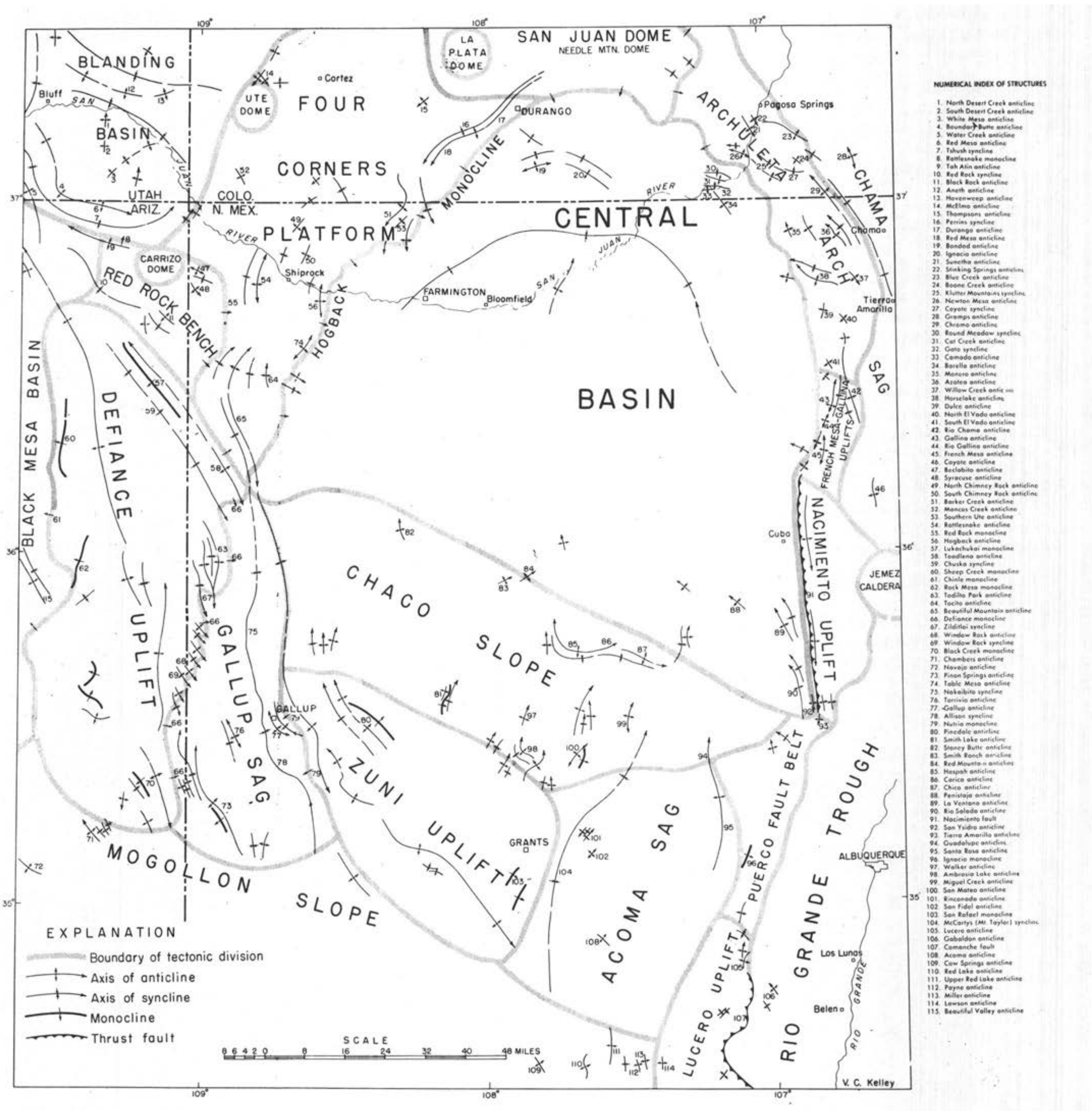


Figure 1

TECTONIC MAP OF SAN JUAN BASIN AND ADJACENT AREAS have been described in connection with regional descriptions (Kelley, 1957, p. 46; Kelley and Clinton, 196o, p. 44-48, 52, 76-81). In addition, some special features of the local structure have been described by graduate students working under the author's direction (Johnston, 1953; Mohar, 1956; Edmonds, 1961). The best description of the structure in the most productive parts of the region is that by Hilpert and Moench (196o, p. 437-444), and the following account is in part taken from them. Reference should also be made to Moench, Thaden and Santos, Laverty, and Rapaport for additional descriptions of the structure elsewhere in this memoir.

The area has been subjected to several minor and one major episode of deformation from Morrison time to the present. The first deformation appears to have accompanied and shortly followed the Morrison sedimentation. Such folds have been described by Kelley (1955, p. 83, 99-10o) and have been mapped by Moench and Schlee in the Laguna area (Hilpert and Moench, p. 439-440). Young (1956, p. 40) and Hilpert and Moench (p. 440-443) have described similar structures in the Ambrosia Lake area. Numerous collapse pipes occur in the Morrison and underlying Jurassic units in the Laguna area. These features are up to 30o feet in diameter and 300 feet high. They appear to base in mudstone and to be related by distribution to some parts of the pre-Dakota folds.

The major deformation of the region probably occurred in Laramide (Late Cretaceous—Early Tertiary) time and gave rise to the Zuni uplift, the San Juan Basin, and the Acoma embayment. At this time, the principal folds and faults in the Grants and Ambrosia Lake areas were formed and the gentle northerly regional dips were established.

Subsequent erosion may have reduced the uplifted areas to lowlands in Eocene time and ensuing deposition covered much of the region with playa or fluvial deposits of a San Jose or Baca type. During mid-Tertiary time continental arching of the region caused extensive stripping, and by late Tertiary time an erosion surface of low relief probably developed across the area at about the level of the Mount Taylor base.

The New Mexico Rockies began their rejuvenation in Pliocene time. The Rio Grande trough was structurally defined, and the faults and associated folds of the Puerco fault belt were formed. The Mount Taylor eruptions developed their modern aspect in late Pliocene time. Concurrently, headward erosion by the Rio Grande tributaries began cutting into the Mount Taylor field. Some of the late eruptions ran into the lowered surfaces such as at Grants and Prieta mesas, which are one or two hundred feet lower than the high mesas such as Chivato and Horace around Mount Taylor. Continued erosion brought the physiography toward its Recent aspect, while late minor faulting broke the older high-level flows in several places. Locally, basalt plugs even domed the high-level basalt flows, as at the San Fidel anticline. Later basalt eruptions in the Zuni Mountains area and near Bluewater sent streams of lava into the valley of the Rio San Jose, which flowed as much as 75 to loo miles to the east into the Puerco Valley.

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MAP SHOWING THE GENERAL STRUCTURAL FEATURES OF THE GRANTS DISTRICT AND THE AREAL DISTRIBUTION OF THE KNOWN URANIUM ORE BODIES IN THE MORRISON FORMATION

ROBERT E. THADEN AND ELMER S. SANTOS

# *Mineralogy*

H. C. GRANGER

## ABSTRACT

Uranium deposits in the Grants mineral belt occur over a wide area in rocks of several ages. Most of the deposits are in the Todilto Limestone, Morrison Formation, or Dakota Sandstone. The mineral assemblages of deposits in each host rock can be divided into unoxidized and oxidized groups that generally correspond to primary and secondary minerals. Minerals in the Westwater Canyon Member of the Morrison Formation, however, can be divided into two groups of unoxidized minerals and two principal groups of oxidized minerals.

Coffinite and uraninite are the most important unoxidized uranium minerals in each of the host rocks. The suites of secondary uranium minerals can vary a great deal, depending in part on local concentrations of vanadium, carbonate, and sulfate ions.

Although the mineral assemblages of the deposits show wide differences in detail, there is an overriding similarity. This similarity may be of even greater importance than the differences when the geochemistry of the deposits is considered.

## INTRODUCTION

Uranium deposits in the Grants mineral belt* (Hilpert and Moench, 196o) occur in a strip nearly 100 miles long and **20** miles wide that extends from near Gallup on the west to Laguna on the east. The deposits extend stratigraphically from the Todilto Limestone of Late Jurassic age to the Dakota Sandstone of Early and Late Cretaceous age. As might be expected, such widespread geographic distribution with such variation in host rocks has resulted in considerable diversity in the mineral assemblages found in the various deposits. This paper discusses briefly these mineralogies within the knowledge of presently available data.

The mineralogy of deposits in the Westwater Canyon Member of the Morrison Formation, as discussed in this paper, is based largely on studies made by the writer, and it is given the greatest emphasis. For the mineralogy of deposits in other stratigraphic units, it was necessary to rely on various sources of information.

Most of the mineral specimens from the Westwater Canyon Member, on which parts of this paper are based, were collected by the writer or E. S. Santos, but some were donated by Robert Smith, Walter Gould, David Smouse, and other mining geologists. Gratitude is also extended to the various mining companies which are active in the Ambrosia Lake are for permission to sample and to report the results.

Although the microscope has been used extensively, the principal means of mineral identification has been by X-ray diffractometer or powder patterns. Many of the minerals, particularly uranium and vanadium minerals, cannot be reliably identified by optical means because of extremely small grain size, opacity, or nondiagnostic optical parameters. To get essentially pure monominerallic samples for identification, it was commonly necessary to employ techniques involving heavy liquids, magnetic separations, and laborious handpicking. The use of an ultraviolet lamp aided in distinguishing certain secondary uranium minerals for handpicking from mixtures. The quality of X-ray patterns was not always good, particularly for some of the minerals of very recent origin on mine walls. The minerals described in this paper, however, are believed to have been reliably identified.

In addition to the primary unoxidized mineral assemblage, some deposits contain redistributed ore bodies which are also composed of unoxidized minerals. Many of the deposits have been subjected to surficial and near-surface weathering, deep oxidation far below the present ground-water table, and recent environmental imbalances imposed by mining both above and below the water table. Each of these has resulted in the formation of mineral groups that are, at least in part, distinctive.

In this report, mineral assemblages have been classified according to whether the associated uranium minerals contain reduced ($U^{+4}$) or oxidized ($U^{+6}$) uranium. Broadly, this divides most deposits into primary and secondary (weathered) mineral assemblages. Where data are available, however, it has been possible to further subdivide these two classes as shown in Table 1.

* The author and others of the U.S. Geological Survey have proposed the term "southern San Juan Basin mineral belt" elsewhere but the "Grants" designation is preferred locally.—V. C. K.

TABLE 1. MINERALS IN DEPOSITS IN THE WESTWATER CANYON MEMBER LISTED ACCORDING TO ENVIRONMENT

| Unoxidized Environment | | Oxidized Environment | | | |
|---|---|---|---|---|---|
| | | Premining | | Postmining | |
| Prefault | Postfault | Deep | Surficial | Efflorescent | Other |
| Carbonaceous material<br>Coffinite<br>Jordisite<br>Pyrite | Coffinite<br>Uraninite<br>Montroseite<br>Paramontroseite<br>Haggite<br>Ferroselite<br>Pyrite<br>Marcasite<br>Barite[1]<br>Kaolinite<br>Calcite | Tyuyamunite<br>Metatyuyamunite<br>Carnotite<br>Gray selenium<br>Cryptomelane | Tyuyamunite<br>Metatyuyamunite<br>Carnotite<br>Red selenium<br>Cryptomelane<br>Autunite<br>Meta-autunite<br>Zellerite<br>Todorokite<br>Gypsum | Zippeite<br>Zippeite-like<br>Andersonite<br>Bayleyite<br>Uranopilite<br>Liebigite<br>Pascoite<br>Green "pascoite"<br>Red selenium<br>Ilsemannite<br>Thenardite<br>Thermonatrite<br>Gypsum | Tyuyamunite[2] |

1. Barite is classified as unoxidized because of its close association with montroseite.
2. X-ray powder pattern has broad lines but is similar to tyuyamunite. Mineral forms under films of water flowing from mine walls.

For complete descriptions of the host rocks and for locations of the various mines mentioned herein, the reader should refer to other papers in this publication.

## DEPOSITS IN THE WESTWATER CANYON MEMBER OF THE MORRISON FORMATION

### UNOXIDIZED ENVIRONMENT.

Sandstones of the Westwater Canyon Member of the Morrison Formation contain unoxidized uranium deposits of twc ages and of somewhat distinctive mineral assemblages (table 2). Primary deposits were formed before the rocks were appreciably jointed or faulted, and they are referred to as prefault deposits (Granger et al., 1961.) Postfault unoxidized deposits probably resulted from redistribution of the prefault deposits, and they are therefore secondary.

The primary, or prefault, deposits are predominantly elongate tubular layers of ore minerals in a gangue of carbonaceous material which cements the sandstones. The carbonaceous gangue is the principal mineralogic feature that distinguishes prefault from postfault deposits. The primary deposits are relatively more resistant to weathering than the postfault deposits and have been found at surface outcrops.

The mineralogy of the prefault deposits is relatively simple, In addition to the carbonaceous material, coffinite, jordisite, and pyrite are the dominant minerals now recognized. Much of the selenium in the deposits seems to occur in a presently unidentifiable form closely associated with jordisite, as described hrein; S. Ralph Austin (196o), however, identified ferroselite in a prefault deposit, and its occurrence may be more common than has been realized. The form of vanadium, which is present in anomalous amounts in most deposits, has not been determined. It seems to occur in the carbonaceous material, and possibly exists as a metallo-organic compound or chelate.

Unoxidized postfault deposits contain somewhat more minerals than the prefault ores, although this may be partly the result of easier recognition permitted by larger grain size and less carbonaceous material among the authigenic minerals of the postfault deposits. Coffinite is by far the most abundant uranium mineral, but pitchblende (uraninite) occurs locally. Vanadium minerals can be recognized, whereas molybdenum minerals are extremely rare or are missing. At least some of the selenium occurs as ferroselite. Pyrite is generally about as abundant as it is in the prefault ore, and marcasite is locally present in fractures. Although calcite cements much of the prefault ore, it seems to postdate the carbonaceous material in all thin sections examined. It commonly fills fractures and much of it is later than the postfault coffinite and montroseite, so that the only calcite that can be reliably dated is postfault in age. Barite is common in many fractures and joints, and it is included with the unoxidized minerals principally because of its close association with unoxidized minerals such as montroseite.

### CARBONACEOUS MATERIAL

The carbonaceous material is an authigenic organic matter that seems to have been introduced in a fluid state and has remained as a precipitate or residue to form grain coatings, interstitial cement, and fracture fillings. This material and hypotheses concerning its origin have been discussed by Granger et al. It is coextensive with prefault ore and seems to be the matrix or gangue in which many of the prefault ore metals occur. The carbonaceous material is generally uraniferous and contains coffinite, but where oxidized, such as in shallow deposits exposed at the surface, the coffinite may be destroyed and the uranium leached. Coalified fossil trunks, limbs, and fragments of wood and grasses may also be ore-bearing, but they are scarce relative to the vast quantities of authigenic carbonaceous material.

Carbonaceous material is not a requisite component of postfault ores as with prefault ores. It is present in very low concentrations, however, in some samples of postfault ore. In most places where carbonaceous material has been detected chemically in postfault ore, it is not visible, even at high magnifications in thinsections. Much of it must occur as stains associated with altered minerals and clays and perhaps as stains in coffinite.

Local asphaltic-appearing fillings in joints are probably derived from nearby prefault ore bodies as they commonly are in border-leached or oxidized zones. Some of this material is uraniferous and contains coffinite but some is evidently nonuraniferous.

### COFFINITE

The carbonaceous material in the prefault ores yields an X-ray pattern for coffinite except where it has been oxidized. The coffinite is exceedingly fine-grained and it has not yet been recognized optically in prefault ore.

Alpha tracks recorded in stripping film applied to uncovered thinsections of prefault ore generally emanate from the carbonaceous material. In some places, however, they emanate from zones of brownish "dust" along the contact between adjacent quartz grains, seemingly where no carbonaceous material has penetrated. Also, some alpha tracks emanate from extremely fine-grained, dark-colored aggregates within strongly altered plagioclase grains. This material may be coffinite, but it is not well enough defined to be identified optically.

Coffinite in postfault ore is extremely fine-grained, but it can commonly be recognized in thinsection and can be separated. It forms aggregates that coat sand grains with a thin film; more rarely it fills small interstices and partly replaces highly altered feldspar(?) grains.

In some reasonably pure separates, the coffinite is brownish gray, but, judging by the color of coatings on sand grains, the coffinite may be less brown in many other samples. Brownish gray coffinite from the Homestake—Sapin Section 15 mine turned light brownish gray when heated to 450° C in the air for 45 minutes; the coffinite structure was destroyed, and the color became yellowish orange when heated to 600° C. This material contained 0.4 percent organic carbon even though the original ore sample, prior to separation, contained 1.03 percent uranium and no detectable organic carbon. The gray of coffinite may be due, in part at least, to organic matter (Fuchs and Hoekstra, 1959).

The coffinite appears as an extremely fine-grained, reddish-brown aggregate when strongly illuminated in thinsections. Individual grains are generally less than 0.005 mm long and 0=1 mm across. The tiny grains all seem to be length slow and indices are near 1.7, which is somewhat less than that for synthetic material.

Table 2.--Authigenic minerals in deposits in the Westwater Canyon Member

| | Towle and Rapaport, 1952 | Rapaport, 1952 | Gruner, Gardiner, Smith, 1954 | Gruner and Smith, 1955 | Gruner and Knox, 1957 | Knox and Gruner, 1957 | Weeks and Truesdell, 1958a | Weeks and Truesdell, 1958b | Konigsmark, 1958 | Thaden and Santos, 1959 | Granger, 1959 | Granger, 1960 | Austin, 1960 | Granger and others, 1961 | Present paper 2/ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$ | | | | X | X | X | X | X | X | X | X | | X | X | X |
| Uraninite, $UO_2$ | | | | | | | X | X | | | | X | | X | X |
| Tyuyamunite, $Ca(UO_2)_2(VO_4)_2.5\text{-}8H_2O$ | | | | | | | | | X | X | X | | | X | X |
| Metatyuyamunite, $Ca(UO_2)_2(VO_4)_2.3\text{-}5H_2O$ | | | X | | X | | | | | | X | | | X | X |
| Carnotite, $K_2(UO_2)_2(VO_4)_2.1\text{-}3H_2O$ | X | X | | X | | | | | | | | | | X | X |
| Zippeite, $2UO_3.SO_3.5H_2O$ | | | | | | | | | | | X | | | X | X |
| Zippeite-like | | | | | | | | | | | | | | | X |
| Andersonite, $Na_2Ca(UO_2)(CO_3)_3.6H_2O$ | | | | | | | | | | | X | | | X | X |
| Bayleyite, $Mg_2(UO_2)(CO_3)_3.18H_2O$ | | | | | | | | | | | | | | | X |
| Uranopilite, $(UO_2)_6(SO_4)(OH)_{10}.12H_2O$ | | | | | | | | | | | | | | | X |
| Liebigite, $Ca_2(UO_2)(CO_3)_3.10H_2O$ | | | | | | | | | | | | | | | X |
| Uranophane, $Ca(UO_2)_2SiO_3(OH)_2.5H_2O$ | | | | | | | X | X | | X | | | | | |
| Autunite, $Ca(UO_2)_2(PO_4)_2.10\text{-}12H_2O$ | | | | | X | | | | X | | X | | | X | X |
| Meta-autunite, $Ca(UO_2)_2(PO_4)_2.8H_2O$ | | | X | | X | | | | | X | | | | X | X |
| Zellerite, ? | | | | | | | | | | | | | | | X |
| Schroeckingerite | 1/ | 1/ | | | | | | | | | | | | | |
| Montroseite, $V_2O_3.H_2O$ | | | | | | | | | | X | X | | | X | X |
| Paramontroseite, $V_2O_4$ | | | | | | | | | | X | X | | | X | X |
| Haggite, $V_2O_3.V_2O_4.3H_2O$ | | | | | | | X | X | | | | | | X | X |
| Corvusite, $V_2O_4.6V_2O_5.nH_2O$(?) | | | | | | X | | | | | | | | | |
| Pascoite, $Ca_3V_{10}O_{28}.16H_2O$ | | | | | X | X | | | | X | X | | | X | X |
| Green "pascoite" | | | | | | | | | | | | | | X | X |
| Jordisite, $MoS_2$ (?) | | | | | | | | | | | X | | X | X | X |
| Ilsemannite, $Mo_3O_8.nH_2O$ (?) | | | | | | | | | | | X | | X | X | X |
| Ferroselite, $FeSe_2$ | | | | | | | | | | X | X | | X | X | X |
| Gray native selenium, Se | | | | | | | | | | X | X | | X | X | X |
| Red native selenium, Se(?) | | | | | | | | | | | X | | X | X | X |
| Pyrite, $FeS_2$ | | | X | | | X | | | | X | X | X | X | X | X |
| Marcasite, $FeS_2$ | | | | | | | | | | | X | | X | X | X |
| Anatase, $TiO_2$ | | | | | | | | | | | X | | X | X | X |
| Galena, PbS | | | X | | X | | | | | | | | | | |
| Barite, $BaSO_4$ | | | | | | | | | | X | X | | | X | X |
| Calcite, $CaCO_3$ | | | | | | X | | | | X | | X | X | X | X |
| Gypsum, $CaSO_4.2H_2O$ | | | | | | | | | | | | | | | X |
| Cryptomelane, $K_2O.MnO.8MnO_2.2H_2O$ | | | | | | | | | | | | | | | X |
| Todorokite, $2(Mn, Ca)O.5MnO_2.4H_2O$ | | | | | | | | | | | | | | | X |
| Goethite, $Fe_2O_3.H_2O$ | | | | | | X | | | | | | | | | X |
| Hematite, $Fe_2O_3$ | | | | | | | | | | | | | | | X |
| Thenardite, $Na_2SO$ | | | | | | | | | | | X | | | X | X |
| Thermonatrite, $Na_2CO_3.H_2O$ | | | | | | | | | | | | | | | X |

1/ Gruner, Gardiner, and Smith (1954) state that the so-called schroeckingerite was misidentified and is actually meta-autunite.

2/ List includes only minerals identified during this study.

Coffinite forming a thin, black, warty surface coating in a fractured fragment of coalified wood was found near the surface in the Poison Canyon mine. Desiccation joints in the fossil wood could have formed at any time in the history of the rock; thus, the age of the coffinite cannot be determined with certainty. The film had a dull, earthy appearance very much like some paramontroseite or todorokite joint coatings.

Where quartz overgrowths are present on sand grains in postfault ore, most of the coffinite overlies the overgrowths, but, in some instances, sparsely distributed grains of coffinite mark the surface of the original rounded quartz grains. Coffinite is commonly associated with montroseite, but the paragenetic relations are generally ambiguous. In the best examples, it appears that montroseite needles are perched on the coffinite layers, but, in other instances, the bases of the needles are surrounded by coffinite. Although much pyrite in the rocks must be earlier than postfault coffinite, in most of the specimens that have been examined, it seems to be later than coffinite.

### PITCHBLENDE (URANINITE)

Pitchblende has been found both below the water table in the Kermac Section 22 mine (Granger, 1960) and well above the water table in the Mesa Top and Poison Canyon mines (Young, 1956). Evidently, it is extremely rare in the sandstones of the Westwater Canyon, and, in all instances, it probably is a postfault mineral. Near all known uraninite occurrences, oxidation has destroyed some pyrite and coffinite.

Few data are available on the Mesa Top and Poison Canyon occurrences, but the pitchblende in the Section 22 mine occurred on the 6400-foot level (mistakenly reported as the 6450-foot level in Granger, 196o, and Granger et al., 1961) in a vug extending along a northwest-trending fracture. Most of the pitchblende formed a hard, black, vitreous, botryoidal crust less than 2 mm thick on the walls of the vug and fracture. The adjacent sandstone contained much disseminated pyrite older than the pitchblende, and the pitchblende was overlain by scalenohedral calcite, which was locally plated with a thin pyrite film. Under a metallographic microscope, minute orbs of pitchblende can be seen included in some of the calcite immediately adjacent to the pitchblende crust, but the fractures in the pitchblende are, in turn, filled with calcite.

### VANADIUM MINERALS

Montroseite, paramontroseite, and haggite are the only low-valent ($V+^3$ and $V+^4$) minerals recognized in the unoxidized Westwater Canyon deposits, and these are found only in the postfault ores. Vanadium clays, chlorites, and hydro-micas may be present but have not been identified. In addition, vanadium may well be present as a vanado-organic material in the carbonaceous gangue of prefault ores, but the mode of its occurrence in these ores has not yet been determined.

Paramontroseite probably occurs only as a pseudomorph after' montroseite (Evans, 1959), which readily oxidizes to paramontroseite after brief exposure to the atmosphere. Specimens of montroseite, even X-ray spindles of montroseite, collected in deep mines at Ambrosia Lake have all changed to paramontroseite after a few months' storage in the laboratory. The occurrences of montroseite and paramontroseite in sandstones of the Westwater Canyon can, therefore, be discussed together; montroseite and haggite are the only unoxidized postfault vanadium minerals yet identified.

Montroseite forms fracture fillings, cement, and dissemination in the ore-bearing sandstones. As a fracture filling, it varies in physical appearance from a firm, grayish black crust to a velvety layer of delicate, black, acicular crystals as much as 1 mm long oriented normal to the fracture surface. Where rubbed, the crystals are readily crushed and smear out to a metallic dark gray surface. The solid crusts of montroseite are rarely more than about I mm thick and range from earthy to botryoidal with a distinctly bladed radiating crystal structure on broken edges. Presumably, the crusted varieties of montroseite form where bladed montroseite has grown so densely as to form a solid mass.

Amorphous-appearing montroseite cements sandstone under the fracture surface coatings and near interfaces between thoroughly oxidized and unoxidized rock. It ranges from a film on sand grains to a thorough impregnation of the pore spaces.

A characteristic feature of most postfault ore, with the exception of the Kermac Section 24 deposit, is the presence of microscopic, single acicular crystals or radiating clusters of montroseite perched on sand grains and projecting into interstices. These blades are commonly about o.05 mm long and rarely exceed twice this size. Coffinite is commonly associated with these occurrences of interstitial montroseite. A black mineral and a medium- to light-brown mineral observed by S. R. Austin (written communication, 1962) occur as "bow-tie" aggregates perched on sand grains but distinct from montroseite. These may be vanadium minerals but remain unidentified.

In fractures, montroseite is commonly associated with radioactive barite and gray native selenium. Inclusions of montroseite in the outer zones of barite crystals and montroseite blades perched on barite show that montroseite started growth during the later stages of, and continued after, barite development.

Interstitial montroseite is associated with coffinite, pyrite, calcite, and kaolinite. Probably montroseite started to crystallize shortly after coffinite and continued to crystallize after coffinite development had ceased, as there are many places where the relation between these minerals is conflicting. In a few places, montroseite is perched on pyrite cubes. Calcite surrounds montroseite and is evidently younger where they are associated. The relations between montroseite and kaolinite are generally not clear, but in most places kaolinite seems to envelop the montroseite in much the same fashion as calcite. Where quartz overgrowths occur, the montroseite generally overlies the overgrowth.

Haggite has been recognized in the Kermac Section 10, the Homestake—Sapin Section I 5, and, by Weeks and Truesdell ( 1 958a), in the Dysart No. 1 (Rio de Oro) mine. Very likely, it occurs in other mines.

Haggite occurs principally perched on sand grains as black, stubby crystals a few thousandths of a millimeter across. This nearly equidimensional shape serves to distinguish it from the more elongate montroseite crystals with which it is generally associated.

Haggite also occurs as a black coating on sand grains near oxidized joints, suggesting that vanadium in the joints was redistributed under oxidizing conditions and precipitated as haggite near the margin of the oxidized zone.

By inference, haggite may have about the same paragenetic relations as montroseite, but the few samples in which haggite has been identified have been unsatisfactory for such study.

## JORDISITE

Amorphous black material which gives molybdenum-rich sandstone a jet-black or dark brown color is believed to be jordisite. It is probably identical with the jordisite described by Staples (1951) from Clackamas County, Oregon, but it has not been positively identified because it is very fine-grained or amorphous, difficult to separate, and gives no X-ray pattern.

Jordisite-rich sandstone in the Westwater Canyon occurs either as elongate rounded zones, as much as several feet long, within or adjacent to the uranium ore layers or as more irregular, ill-defined zones that commonly "feather out" along cross-bedding and occur both above and below ore layers.

Jet-black jordisite seems to be the dominant type, and the brown varieties may be the result of alteration or of associated organic matter. Some of the jordisite-rich sandstone contains significant amounts of carbonaceous material which is ordinarily uraniferous. Much of it, however, is nearly carbon and uranium free, even though it may occur only inches from a carbon- and uranium-rich prefault ore layer.

Jordisite occurs almost exclusively with prefault ores. Most postfault uranium ore bodies, in fact, contain no detectable molybdenum. If the postfault ores were derived by redistribution of prefault ores, molybdenum must have been lost in the process.

In thinsections, jordisite is seen as tiny, ragged-looking grains less than o.001 mm in diameter which coat the sand grains. Their aspect in different thinsections ranges from opaque black to dark brown. In many places, jordisite cannot be distinguished unequivocally from carbonaceous material under the microscope.

Many samples that are rich in jordisite are also rich in selenium. The Se: Mo ratio, however, is quite inconstant. The form in which selenium occurs in these samples is not yet known.

Paragenetic relations of jordisite are not readily defined because jordisite is easily confused with carbonaceous material and, perhaps, with other black, opaque constituents. Although no jordisite has been seen coating pyrite, areas where pyrite impinges on the sand grains seem to be free of jordisite. They may have formed simultaneously. Pyrite associated with calcite and other late minerals is much later than jordisite.

In the Marquez mine, jordisite is older than quartz overgrowths (Randall Weege, oral communication, 1959). Elsewhere, except for one thinsection from the Bucky No. I mine, thinsections generally show jordisite coating quartz overgrowths where both are present.

## FERROSELITE

Ferroselite has been found in two localities at Ambrosia Lake, but very likely it is more widespread. Determined efforts to isolate it in other places would probably prove fruitful.

In the Homestake—Sapin Section 15 mine, ferroselite coats scalenohedral calcite crystals that project into a fracture; hence, ferroselite is here classed as a postfault mineral.

In the Section 15 mine, bright, metallic, silvery, prismatic or rod-shaped crystals of ferroselite are set in, and project from, a matrix of claylike material. The aggregate forms a coating on the calcite crystals less than o.3 mm thick in which the ferroselite crystals are more abundant near the surface of the aggregate than near the calcite.

X-ray patterns of the claylike matrix establish the presence of major goethite and very minor quartz. The admixture of fine-grained goethite with the ferroselite gives the mass a yellowish cast which resulted in a description (Granger et al.) crediting ferroselite with a pyritelike, metallic-yellow color.

The other reported occurrence of ferroselite is in the Marquez mine where S. Ralph Austin identified it by X-ray methods in a black ore sample with a high molybdenum content. This ferroselite must be prefault in age because it is associated with jordisite and because no postfault ore is known in the Marquez mine.

## PYRITE AND MARCASITE

Pyrite is generally plentiful in both prefault and postfault ores, but marcasite seems to be present only in faults and fractures. Where pyrite is disseminated in the ores or in barren sandstone, it is generally difficult, if not impossible, to distinguish prefault from postfault varieties. Pyrite that is earlier than carbonaceous material in a prefault ore body is, of course, also earlier than the faults. In addition, it is arbitrarily assumed that inclusions of pyrite in highly altered detrital grains and pyrite replacements in mudstone and coalified wood are also prefault, although direct proof may be lacking.

Prefault pyrite occurs both as disseminated discrete grains, many of which are nearly euhedral, and aggregates of anhedral grains. Pyrite enclosed in carbonaceous material is corroded(?) and generally anhedral, but subhedral cubes have been noted. Most grains are smaller than fine sand. Highly altered, unrecognizable detrital grains commonly contain myriads of tiny, discrete, euhedral cubes of pyrite, suggesting that the altered mineral was originally iron rich.

Pyrite in mudstone is commonly euhedral, and the cubes locally attain a size of 0.5 cm on a side. In addition, masses of anhedral pyrite and subhedral aggregates that face into small, curved fractures have been noted. These fractures may have been caused by compaction or by forces related to the swelling of montmorillonite in the mudstone rather than by faulting.

Most of the pyrite in coalified wood is along discontinuous fractures and small solution cavities. It is commonly subhedral to anhedral. Anhedral to euhedral pyrite also forms minute discrete grains that partly replace the cell walls in some specimens.

Postfault pyrite occurs both in joints and fractures and is disseminated throughout the sandstone. The disseminated pyrite may be difficult to classify, but, where rocks adjacent to a fracture contain more pyrite than at some distance away, it seems obvious that the pyrite is later than the fracture. The disseminated postfault pyrite seemingly has no distinctive characteristics that aid in distinguishing it from prefault varieties, although the sparse occurrence of octahedrons or octahedral faces may be a criterion.

In fractures, pyrite generally occurs sporadically as drusy aggregates and porous masses. The grain size rarely exceeds 0.5 mm, and the smallest grains are microscopic. Cubes, octahedrons, and combinations of these are the most common crystal forms. Very rare modifications of octahedrons by minute pyritohedral faces have been noted, but no well-formed pyritohedrons are present.

In a few places, such as the Kermac Section 23 and the Poison Canyon mines, relatively late-stage coatings of pyrite give a gold-plated appearance to calcite crystals which project into cavities along the fault and fracture zones. Under the metallographic microscope, the pyrite shows no well-developed crystal forms and appears to be a very thin microbotryoidal film with a somewhat scaly surface. X-ray patterns show that minor marcasite accompanies the pyrite.

Marcasite has been noted only in fractures, and it is generally associated with pyrite. Locally, however, areas within a fracture are filled with a monomineralic aggregate of marcasite grains. Marcasite crystals are generally subhedral with poorly to well-developed (oo ) and (I I o) faces. Typical grains are either nearly equidimensional with prominent (001) faces or are tapering, prismlike forms either lying parallel to the joint surface or projecting outward. Ordinarily, the grains are no more than o.5 mm in their longest dimension, but larger ones have been noted.

Pyrite and marcasite seem to be very poor index minerals for determining paragenetic relations as they evidently formed at several different stages in the history of the rocks. For the most part, pyrite preceded calcite in deposition. Fracture walls are commonly coated with a drusy surface of pyrite and the remaining space is filled with calcite. Where postfault pyrite is disseminated in the sandstone, it seems also to be earlier than montroseite, which is perched on the pyrite grains in places. Although very obscure, the relations between postfault coffinite and pyrite generally indicate that the coffinite preceded postfault pyrite. In the one example available, pitchblende was deposited after most of the pyrite, but a little pyrite was deposited on calcite grains that followed the pitchblende deposition. Kaolinite is later than pyrite wherever a relation was observed.

## CALCITE

Calcite occurs as a cement in the sandstone, as a fracture filling, and as limestone associated with mudstones. Only where it fills a fracture can calcite be reliably dated as postfault. On the other hand, there is no good evidence for the existence of prefault calcite, with the exception of the limestone layers which are considered to be syngenetic with the enclosing rocks.

In the Black Jack No. I mine, and in a few places elsewhere, large, rounded, calcite-cemented concretions, as much as several feet across, occur in the barren sandstone. These could be of any age, as no relation to faults or features of known relative age has been noted.

A variety of prefault ore, locally termed "mottled ore," may have been controlled in part by pre-existing calcite in the host rock. Mottled ore forms zones as much as a few feet across in and at the margins of black, prefault ore layers. It is characterized by many irregular, rounded, unmineralized spots from a few millimeters to 1.5 cm across. Although the entire rock is now usually calcite-cemented and calcite grains pass indiscriminately across the boundary between barren rock and ore, it is believed that these barren spots may represent sandstone that was partly calcite-cemented at the time the carbonaceous material was deposited.

Calcite commonly cements the first few inches or feet of sandstone directly overlying a mudstone layer. It is locally an abundant cement in and adjacent to prefault ore layers. Large "poikiloblastic" grains range in size from a few millimeters to as much as 4 by 6 inches where exposed on the mine walls; that is, the calcite cement forms a mosaic of large, optically continuous crystals that include many sand grains. At the outcrop, calcite-cemented sandstones commonly weather to a knobby surface, and, in some places, round "marbles" of calcite-cemented sandstone are scattered on the surface. In all thinsections examined, calcite cement fills the interstices that remained after the carbonaceous material coated the sand grains. Perhaps, therefore, all the poikiloblastic calcite cement now seen is postfault.

Calcite is common as a discontinuous and partial filling in many joints and fractures. Locally, it completely fills some openings, but, ordinarily, scalenohedral crystals not more than 2 or 3 mm long form a drusy surface.

Calcite crystals with rhombic faces forming a thin coating on the walls of fractures have been noted only in the Homestake—Sapin Section 15 mine. They are in limonitic sandstone in which all of the pyrite has been oxidized. Very likely, the calcite was deposited after the oxidation, for the acidic environment produced during oxidation would probably have dissolved any calcite present. Generally, calcite is absent in fractures in oxidized rock.

It should be re-emphasized that there is no reliable evidence that any of the calcite in the rock, other than in limestones, is prefault in age. The mobility of calcite makes it even less of a satisfactory index mineral for paragenetic relations than pyrite.

## BARITE

Prefault barite is quite scarce or missing, and it has no diagnostic features. Barite that is inferred to be prefault in age occurs as amber crystals associated with pyrite in siliceous coalified wood in the Kermac Section 30 mine, as a few grams o white crystals in a cavity in a mudstone boulder in the Marquez mine, and as sparse amber blebs as much as 2 inches across in mudstone in the Kermac Section 33 mine.

Most barite is postfault, and all radioactive barite is postfault. With one exception, all the postfault barite seems to occur as small euhedral to subhedral crystals in joints and small fractures. The exception noted was a mass of several tens of pounds of coarsely crystalline, white to clear, anhedral, vuggy barite in a fault zone in the Kermac Section 22 mine. Some of the exposed crystal faces were sparsely coated with limonite-stained tyuyamunite, but the barite itself was not radioactive.

The small plates of barite and radioactive barite, common in joints and fractures of postfault ore deposits, are generally less than 2 mm across, but they can be as much as 5 mm on the edge. They range from yellowish white through clear and cloudy amber to brown, and many are prominently zoned. The radioactive barites are radioactive only near the surface of the outer zone.

Barite generally predates other minerals with which it is closely associated, except for calcite that seems to have been deposited concurrently in places. Montroseite, in some places, started growth during barite deposition, but where both are present, most of it seems to overlie barite. Gray native selenium is later than barite, and, locally, a little pyrite was deposited after barite. Very likely, however, the strongly colored barite was derived from iron sulfate solutions formed by the oxidation of pre-existing pyrite.

## KAOLINITE

Kaolinite in the Westwater Canyon has three distinctly different modes of occurrence of at least two different ages, none of which can be directly related to uranium ore occurrences. Most common are spotty, rounded aggregations of kaolinite referred to as "nests" by Knox and Gruner (1957) and others. These are scattered discrete zones as much as 2 cm across in which all the interstices within the sandstone are filled with kaolinite. Where best developed, these nests are only a few centimeters apart in coarse-grained sandstone and average about 1 cm in diameter. In fine-grained sandstone, where carbonaceous material or other clay minerals partly or completely fill the interstices, the nests may be missing or only a fraction of a millimeter in diameter.

It is very improbable that the kaolinite was derived from nearby altered feldspars. In general, the K-feldspars in the sandstone are not highly altered. The calcic plagioclases are commonly altered, but, generally, they are altered to sericite (Knox and Gruner) or other minerals, suggesting that the alteration may have occurred prior to sedimentary deposition. Altered feldspars are, in many instances, partly replaced by carbonaceous material which everywhere sems to be earlier than the kaolinite. Austin relates the kaolinite to nearby altered feldspars but notes the difficulties of interpreting conflicting relationships in these sandstones.

Probably closely related to the kaolinite nests are fractures as much as 5 mm wide filled only with kaolinite. Most are short joints in partly coalified wood fragments; kaolinite in joints in sandstone is less common.

Kaolinite nests, and probably the fracture fillings also, seem to be late in the paragenetic sequence. They are later than carbonaceous material, most, if not all, pyrite, and montroseite. The relation with calcite is indeterminate in most places, and calcite and kaolinite may be nearly contemporaneous. Knox and Gruner state that calcite is ordinarily later than kaolinite although, locally, the reverse may be true. Most weathering effects seem to have occurred later than the kaolinite nests, but, in a few places, kaolinite is unstained by surrounding disseminated hematite.

Kaolinite is locally abundant in the Westwater Canyon Sandstone Member where it is overlain by the Dakota Sandstone, particularly where the basal part of the Dakota contains coal or carbonaceous shale (Granger, 1962).

## OTHER MINERALS

Other alteration and authigenic minerals, in addition to those already described, occur in the Westwater Canyon, but they are rarely closely related to the uranium deposits. Among these are several iron and titanium minerals that were very likely derived from the destruction of heavy, black, opaque detrital minerals in the sandstone. Alteration of the sandstone is more thoroughly discussed by S. **R.** Austin.

## OXIDIZED ENVIRONMENT

Oxidized minerals that were formed before mining was initiated in the Westwater Canyon Member compose a group that is essentially distinct from minerals that have formed within the mine workings. The premining minerals are generally of moderate to low solubility in ordinary ground waters, whereas the postmining minerals are, for the most part, efflorescent minerals that dissolve readily in water, particularly acid water. To some extent, the premining minerals can also be divided into two groups based on their position relative to near-surface weathering. These groups, however, overlap each other, and the differences may lie partly in sampling rather than in actual differences in the assemblages.

Oxidized uranium minerals that have been identified in the Westwater Canyon consist of vanadates, carbonates, sulfates, and phosphates. For descriptive purposes, the uranium minerals will be discussed in terms of these groups, although the environments in which they occur may not be mutually exclusive.

## URANIUM VANADATES

Tyuyamunite and metatyuyamunite are common constituents of oxidized parts of several deposits, particularly of the postfault deposits. These minerals predate the mining, but a tyuyamunite-like mineral has also been seen which formed after the mining was commenced. All are a bright yellow but tend to acquire a faint orange cast on prolonged exposure.

There is no distinctive difference in habit between tyuyamunite and metatyuyamunite, and it is presumed that they change, one to the other, under the influence of changes in the humidity. As shown by X-ray examination, samples from below the water table commonly contain a predominance of tyuyamunite, whereas samples from above the water table generally contain more metatyuyamunite.

Tyuyamunite and metatyuyamunite have several modes of occurrence: They are disseminated throughout the sandstone where postfault ores are extensively oxidized, they coat fracture surfaces where the earlier montroseite filling is oxidized, and they impregnate the sandstone adjacent to and in zones of cryptomelane accumulations.

In fractures, these minerals commonly form a crust, about 0.25 mm thick, of closely packed micaceous flakes generally oriented normal to the fracture surface.

Small plates of disseminated tyuyamunite and metatyuyamunite about 0.2 mm on a side and 0.02 mm thick occur singly or as aggregates in the interstices among sand grains in oxidized rocks, particularly postfault ore, in which the pyrite has been converted to limonite or hematite. Disseminated tyuyamunite and metatyuyamunite also are associated locally with accumulations of cryptomelane in either mudstone or sandstone.

A very fine-grained, earthy yellow, tyuyamunite-like mineral developed on the mine walls in parts of the Kermac Section 22 mine shortly after the workings were opened. It formed in the interstices of the sandstone at the exposed surface, and for several inches into the rock, under films of water that drained from large postfault ore bodies. The X-ray powder pattern of this material is similar to the tyuyamunite pattern, but the lines are broad, and the intensities and some of the spacings differ considerably from the standard patterns of tyuyamunite.

Carnotite is a comparatively scarce mineral in the Westwater Canyon deposits. In the Kermac Section 22 mine, a small amount of well-crystallized carnotite was found about feet below the ground-water table in a generally faulted area. A fracture surface was sparsely coated with aggregates of crinkled, medium pale yellow flakes with adamantine luster oriented normal to the surface. This is the only known occurrence of carnotite in the Westwater Canyon below the water table.

Three other samples containing carnotite have been collected from deposits that are at or near the outcrop and well above the water table. In the Poison Canyon mine, powdery yellow carnotite fills joints in the silicified core of a partly coalified fossil log. In the Alta mine, about 6 inches below the top of the ore-bearing sandstone, is a layer that is intermittently cemented by cryptomelane. Carnotite is abundantly disseminated in the cryptomelane, in places, but is commonly not readily apparent. In the Dakota mine, mixed carnotite and tyuyamunite are sparsely disseminated throughout highly oxidized rock containing yellowish brown to red goethite.

Paragenetically, tyuyamunite, metatyuyamunite, and carnotie form at any time during oxidation. In most places, they are not closely associated with other oxidized minerals with the exception of iron oxides. Where relations have been observed, tyuyamunite and metatyuyamunite are perched on and are later than barite. They are about the same age as cryptomelane and are, at least in part, earlier than native gray selenium, which is locally perched on tyuyamunite grains.

## URANIUM CARBONATES

Andersonite, bayleyite, liebigite, and an undescribed mineral, "zellerite" (R. G. Coleman, written communication), have been identified in the Westwater Canyon rocks. Several other minerals associated with these uranium carbonates remain unidentified. These may be new minerals and will not be described here.

Andersonite, which is probably the most abundant uranium carbonate in the district, forms clear, light green crystals and aggregates with a bright yellow-green fluorescence. All observed occurrences of andersonite have been on mine walls where it forms a discontinuous fine-grained coating of minute semirounded aggregates less than 1 mm across that coalesce with other such aggregates to form a warty surface. It is commonly associated with thenardite.

Bayleyite was identified in only one sample from the Homestake—Sapin Section 23 mine, but it may be more prevalent. It forms a light yellow crust with a somewhat warty surf arce on the mine wall. Apart from a few grains of admixed andersonite that fluoresce brilliantly, most of the bayleyite crust has only a weak fluorescence under long-wave ultraviolet light and is nonfluorescent under short-wave light. The crust is composed of a matte-like aggregate of extremely small, unoriented, hairlike fibers less than o.5 mm long.

Liebigite has been identified in only one sample from the Kermac Section 22 mine. The liebigite is a bright yellow-green with a greenish fluorescence, and it forms a thin efflorescent crust composed of an aggregate of very small crystals immediately intergrown with gypsum.

The mineral "zellerite" is a uranium carbonate that has tentatively been named and described from an occurrence in the Gas Hills, Wyoming (R. G. Coleman, written communication). The four strongest lines on the X-ray pattern of a seemingly identical mineral from the Alta mine have d-values (A) of 9.12, 3.8o, 4.72, and 4.29. In contrast to the other uranium carbonates, "zellerite" is a premining mineral that occurs as a very fine-grained aggregate intergrown with gypsum in bedding-plane fractures. It also forms thin, warty, microbotryoidal crusts and minute hemispherical aggregates in openings along these fractures. "Zellerite" is yellow with a pale greenish yellow fluorescence.

## URANIUM SULFATES

Zippeite and zippeite-like minerals are the most common uranium sulfates in the sandstones of the Westwater Canyon but uranopilite has also been recognized. All the uranium sulfates seem to have formed after mining was initiated. They are formed on mine walls in both pre- and postfault deposits but are most common on high-grade ore in prefault deposits.

Zippeite typically forms minute "pincushions" consisting of hemispherical aggregates of radiating needles. These are generally less than 0.5 mm in diameter and locally coalesce to form a bright yellow to orange-yellow, earthy-looking coating or crust. Most zippeite is nonfluorescent or has a weak yellow fluorescence.

A zippeite-like mineral with X-ray pattern identical to that of a uranium sulfate in the Happy Jack mine, Utah (Frondel, 1958, p. 146), is about as abundant as zippeite and commonly occurs mixed with zippeite. In contrast to zippeite, this mineral appears to form unoriented flaky aggregates in which the individual crystals are of clay-particle size. It also forms earthy yellow crusts composed of coalesced hemispherical aggregates of minute grains. Fluorescence is variable from sample to sample and ranges from nonfluorescent to bright yellow-green.

Both zippeite and the zippeite-like mineral are commonly associated with clear to white and brownish efflorescent micro-crystalline aggregates that have not been identified. For the most part, they seem to be sulfates, largely iron sulfates, but the X-ray patterns differ from place to place and do not seem to match the standard patterns of common minerals.

Uranopilite has been identified in only two mines (table 3), but it looks so much like zippeite that it may have been overlooked elsewhere. It is lemon yellow to greenish yellow and is generally a brighter hue than zippeite. It fluoresces a brilliant greenish yellow. The efflorescent coatings of uranopilite consist largely of scattered hemispherical microcrystalline aggregates with a finely felted to claylike appearance, similar to zippeite.

## URANIUM PHOSPHATES

Uranium phosphate minerals are rather scarce in the Westwater Canyon rocks, in spite of the fact that they were among the first oxidized uranium minerals recognized. A mineral at the Blue Peak mine first believed to be schroeckingerite (Towle and Rapaport, 1952) was later identified as meta-autunite (Gruner, Gardiner, and Smith, 1954). Both autunite and meta-autunite have now been identified from this locality and at the Poison Canyon mine, but they are not known to occur elsewhere in the Westwater Canyon. Both localities are at or near the outcrop in the so-called "Poison Canyon sandstone" of Zitting et al. ([1]957, p. 55, 57).

Frondel implies that meta-autunite forms only by dehydration of autunite, which can take place at or near ordinary conditions of temperature and humidity. Perhaps, therefore,

Table 3.--Authigenic minerals in deposits in the Westwater Canyon Member, listed by locality

| Mine name | Carbonaceous material | Coffinite | Uraninite | Tyuyamunite | Metatyuyamunite | Carnotite | Zippeite | Zippeite-like | Andersonite | Bayleyite | Uranopilite | Liebigite | Autunite | Meta-autunite | "Zellerite" | Montroseite | Paramontroseite | Haggite | Pascoite | Green "pascoite" | Jordisite | Ilsemannite | Ferroselite | Gray native selenium | Red native selenium | Barite | Cryptomelane | Todorokite | Thenardite | Thermonatrite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kermac Sec. 10----- | C | | | | | | | | | | | | | | | X | V | X | V | | | | | | | V | | | | |
| 17----- | C | X | | | | | | | | | | | | | | | | | | | V | | | | | V | | | | |
| 22----- | C | | X | X | X | X | | | X | | | X | | | | | V | | V | | | | | V | V | X | | | X | X |
| 24----- | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 30----- | C | | | | | | ? | | X | | | | | | | | | | | | V | | | | ? | V | | | | |
| 33----- | C | | | | | | | | | | | | | | | | | | | | V | | | | | V | | | | |
| Phillips' Sec. 28-- | C | X | | | | | | | X | | | | | | | | | | | | V | V | | | | V | | | X | |
| 34-- | C | | | | | | | | | | | | | | | | | | | | V | | | | | | | | | |
| 36-- | C | X | | X | | | | | | | | | | | | | | | | | | | | | | | X | | | |
| Doris No. 1-- | C | | | | | | X | | | | X | | | | | | | | | | | | | V | | | | X | | |
| Isabella----- | | X | | | | | | | | | | | | | | | V | | | | | | | | ? | V | | | | |
| Homestake Sec. 15-- | C | X | | X | X | | | | X | | | | | | | | X | X | X | X | | | X | X | V | X | | | X | |
| 23-- | C | X | | X | X | | | X | | X | | | | | | | V | | | | V | | | V | V | | X | | | |
| 25-- | C | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | |
| 32-- | C | | | | | | | | | | | | | | | | | | | | V | V | | | | | | | | |
| 32-29-- | C | | | | | | | | | | | | | | | | | | | | V | V | | | | | | | | |
| Dysart No. 1------- | C | 2/ | | X | X | | | | | | | | | | | | X | 5/ | V | V | V | | | | | V | | | | |
| Bucky No. 1-------- | C | | | | | | X | X | | | | | | | | | | | | | V | V | | | | | | | | |
| Mary No. 1--------- | | | | | | | | | | | | | | | | | | | V | | | | | | | | | | | |
| V.C.A. mine-------- | C | | | | | | | | | | | | | | | | | | | | V | V | | | | | | | | |
| Hogan-------------- | C | X | | | | | | X | | | | | | | | | | | | | V | | | | | | | | | |
| Dog No. 1---------- | C | | | | | | | | | | | | | | | | | | | | V | V | | | | | | | | |
| Marquez------------ | C | X | | | | | X | | | | | | | | | | | | | | V | V | 6/ | X | V | X | | | | |
| San Mateo---------- | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Rialto------------- | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Mesa Top----------- | C | 4/ | 3/ | | | | X | | | | | | | | | | | | | | V | V | | | | | | | | |
| Poison Canyon------ | C | X | 3/ | 4/ | 1/ | X | | | | | | | X | X | | | V | | V | | | | | X | | V | | | | |
| Blue Peak---------- | C | 4/ | | 4/ | | | | | | | | | X | X | | | | | | | ? | | | | | | | | | |
| Dakota------------- | | | | X | | X | | | | | | | | | | | | | | | | | | | | | | | | |
| Taffy-------------- | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Alta--------------- | V | 4/ | | 4/ | | X | | | | | | | | | X | | | | | | | | | | | | X | | | |
| Black Jack No. 1--- | C | | | X | X | | | | | | X | | | | | | | | | | V | | | | V | | X | | | |
| Church Rock-------- | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Identification was by recognition (V), X-ray pattern (X), or chemical means (C).

References are listed for minerals not identified during this study.

1/ Gruner, Gardiner, and Smith, 1954

2/ Young and Ealy, 1956

3/ Young, 1956

4/ Konigsmark, 1958

5/ Weeks and Truesdell, 1958a

6/ Austin, 1960

the collected samples of meta-autunite were actually autunite at or shortly before the time of collection. All the autunite seems to have formed before mining was commenced.

At the Blue Peak deposit, autunite largely occurs associated with mudstone. Two modes of occurrence have been noted. In the first of these, the autunite forms bright yellow microcrystalline blebs, less than z mm across, completely embedded in gypsum, which fills bedding-plane fractures about 5 mm thick in mudstone layers.

In the second mode of occurrence, autunite forms bright greenish yellow, rounded, wafer-thin plates on the surface of joints in mudstone. The plates are composed of fanlike radiating aggregates, 2 to 8 mm in diameter and only about 0.10 mm thick, of small micaceous autunite grains.

At the Poison Canyon mine, autunite occurs as scattered, clear green platy flakes on the surfaces of fractures in the coalified rind of a partly silicified fossil log in an open cut quite near the original surface outcrop.

The various samples of autunite fluoresce a brilliant green to yellow green, whereas the mixed samples of meta-autunite fluoresce paled greenish yellow to yellow.

## VANADIUM MINERALS

With the exception of the uranium vanadates, the only highly oxidized vanadium minerals identified in the deposits are various forms of pascoite. Yellow, orange, blue, and green stains, however, are quite common on the mine walls, particularly in postfault ore bodies, and many of these are known to be caused by vanadium compounds.

Pascoite generally occurs as earthy, orange, efflorescent coatings and brittle crusts on the mine walls. More rarely, it occurs as dark brown radiating aggregates made up of minute granular crystals. The minute crystal faces are oriented in such a way that areas as much as 2 cm long on the mine wall seem to be made up of a single crystal face. These composite faces, in turn, form radiating fan-shaped clusters. Both the orange and brown varieties of pascoite produce a yellow powder wherever they are scratched or pulverized.

A pascoite-like mineral, referred to as green pascoite (Granger et al.), has been noted in a few places and ordinarily forms small scattered excrescent aggregates of olive-green crystals associated with orange pascoite on the mine walls. Some of these have grown under a bubble-like covering on typical orange pascoite.

Some vanadium compounds form a blue stain on mine walls in postfault ore bodies where the vanadium to uranium ratio is relatively high. The color is similar to the blue of ilsemannite, but no molybdenum is present.

## SELENIUM MINERALS

Oxidation of reduced selenium minerals commonly results in the release of native selenium which occurs in two forms, gray and red. Gray native selenium is common in some of the deposits in premining oxidized environments. Red native selenium, however, occurs almost exclusively as a surficial stain on mine walls.

Gray native selenium occurs largely in fractures from well above to at least 200 feet below the premining ground-water level. It forms needles as much as about 1 cm long, but generally they are much shorter with a remarkably uniform cross section about 0.02 mm in diameter. Megascopically, the needles are metallic steel gray. Under medium-power magnifications, the needles are black to metallic gray in reflected light and black opaque in plane polarized transmitted light. However, under crossed nicols and in strong illumination, they are ruby red on the edges.

In open spaces, gray native selenium generally forms a velvety mass of needles oriented normal to the surfaces on which they grow. Locally, septa of short crystals connect the fracture walls, and longer crystals grow outward from the septa subparallel to the fracture.

The sandstone typically is strongly oxidized close to gray native selenium, and concentrations of gray selenium are greatest just beyond the oxidation front. An exception was noted in the Marquez mine where native selenium forms a bright, silvery, metallic film streaked in the direction of movement along randomly curved fracture surfaces within mudstone galls (*see also* Sun and Weege, 1959). There was a little red selenium stain but no limonite or hematite in the sample collected, and none was noted in the nearby rocks.

Gray native selenium commonly occurs alone but may be associated with barite, which is earlier, or calcite. Specimens from a fault zone in a postfault ore body in the Poison Canyon mine contain selenium needles perched on barite plates that are in turn perched on scalenohedral calcite crystals. Elsewhere in the same fault, the calcite crystals are plated with a thin film of pyrite and marcasite.

Red native selenium occurs as an efflorescent stain that colors exposed rock surfaces. Most of it is found on mine walls; hence, it probably developed after mining. The identification is based on color, which is a little brighter than most hematite, the qualitative presence of selenium, and the fact that one form of native selenium is red. The red film is too thin to separate for study, and some of it may actually be a selenium salt.

The red native selenium is not generally associated with gray selenium, but it develops in ill-defined areas not readily related to distinctive lithology, stratigraphy, uranium ore, or fracturing. Its abundance near the ferroselite occurrence in the Homestake—Sapin Section 15 mine suggests that it may be derived from oxidized ferroselite.

## MANGANESE OXIDES

The manganese oxides, cryptomelane and todorokite, have been identified in the deposits but are generally not abundant. Cryptomelane is not readily distinguished from psilomelane except by X-ray means. X-ray patterns of samples from the Westwater Canyon deposits seem to match cryptomelane. In addition, the material is seen to be crystalline in polished section, whereas psilomelane generally appears to be amorphous (Ramdohr, 1956). Both cryptomelane and todorokite are black and opaque, but cryptomelane mostly forms a cement in sandstone or replaces mudstone, whereas todorokite occupies fractures. Cryptomelane is relatively abundant in the Alta mine where it forms a layer of cement in sandstone about six inches below mudstones of the Brushy Basin Member. The sandstone is strongly oxidized above the cryptomelane layer and only partly oxidized below it. The cement is heavy, black, and massive appearing, but small, disseminated voids contain carnotite and metatyuyamunite, making it seem that the cryptomelane is radioactive.

Most other occurrences of cryptomelane are in mudstone galls embedded in partly oxidized sandstone. The cryptomelane partly replaces the mudstone in a zone that separates the unoxidized core of the mudstone gall from the oxidized rind. It forms irregularly shaped patches and occurs along short fractures. Some of this cryptomelane is highly radioactive, but, as the uranium content is negligible, it is assumed that radium is the cause of most of the radioactivity (Granger, 1963).

In the Phillips' Cliffside mine, nonradioactive cryptomelane fills very narrow fractures in a well-oxidized fault zone about 000 feet below the ground-water table.

Todorokite has been found only in the Doris No. 1 mine where it forms coatings on fracture surfaces in a fault zone about 100 feet beneath the surface. As most of the sandstone within the mine is partly oxidized, the todorokite may be the result of near-surface weathering. The todorokite consists of concentric-shelled pisolitic aggregates, mostly less than 0.05 mm in diameter, clustering into a velvety black, microbotryoidal crust that coats the fracture surface. The interior of the crust is dull dark gray to black.

## OTHER OXIDIZED MINERALS

The only other oxidized minerals of any consequence identified to date are thenardite, thermonatrite, and gypsum. Several efflorescent minerals remain unidentified, but some of these seem to be iron sulfates in various states of hydration.

Thenardite is quite common in well-ventilated parts of mines below the water table where seepage is significant but balanced by evaporation. It forms white crystalline crusts and delicate lacy accumulations, as much as one inch thick, made up of interconnected needlelike crystals. By the time the samples have been returned to the laboratory for analysis, the clear to white crystals have become a white powder, and it is likely that the mineral found underground is a hydrated form of sodium sulfate rather than thenardite.

Thenardite is associated with andersonite and, perhaps, other uranium carbonates, unidentified iron sulfates (?), and thermonatrite. The thermonatrite was mixed with, and was not distinguished from, the thenardite in the field.

Gypsum is abundant in near-surface deposits, particularly in mudstones, as a premining product of weathering. It locally forms typical selenite crystals, which weather out on the surface of the Brushy Basin Member, and also forms columnar fracture fillings, in which the columns are oriented normal to the fractures. Most of the gypsum-filled fractures are bedding-plane fractures, as much as an inch or so wide, in mudstone lenses in the Westwater Canyon Member and in the Brushy Basin Member.

Although gypsum is abundant as a premining mineral near the surface, it is rare or absent in the deeper deposits. Most of the gypsum identified in the deep deposits in the Westwater Canyon Member occurs as efflorescent coatings on mine walls or as interstitial crystals in the sandstones within the first few inches back from the wall surface. Efflorescent gypsum, like many of the efflorescent uranium minerals, occurs as microbotryoidal crusts composed of coalesced hemispherical aggregates of minute clear crystals perched on the mine walls.

# DEPOSITS IN THE JACKPILE SANDSTONE (OF ECONOMIC USAGE) MORRISON FORMATION

## UNOXIDIZED ENVIRONMENT

Most uranium deposits in the Jackpile sandstone (of economic usage) are tabular elongate masses of sandstone cemented by uraniferous carbonaceous material quite similar in most respects to deposits in the Westwater Canyon. At least one deposit, however, the Woodrow, is controlled by a cylindrical collapse structure and differs both in shape (Hilpert and Moench) and mineralogy from typical sandstone deposits in the mineral belt. The mineral assemblages are, therefore, distinguished for comparison (table 4).

The dominant unoxidized uranium mineral in both the tabular deposits and the Woodrow deposit is coffinite (Moench, written communication, 1963). Most of the coffinite is finely disseminated on a submicroscopic scale in the carbonaceous material that impregnates the sandstones and in coalified wood fragments. Rare, relatively coarsely crystallized, fibrous, spherulitic coflinite was found in a vug in the Woodrow deposit (Moench, 1962).

Uraninite, although subordinate to coffinite, has been found in most deposits in the Jackpile sandstone. Nearly all specimens that contain coflinite also contain a little uraninite (Moench, written communication, 1963). Most of the coffinite although the X-ray powder patterns of coffinite are characteristically sharp, the uraninite lines are diffuse.

The deposits in the Jackpile sandstone, where uraninite seems to be common if not abundant, may be comparable to those in the Westwater Canyon Member, in which uraninite occurs near partly weathered or oxidized primary coffinite. Most of the uranium deposits in the Laguna district are oxidized to some extent (Moench, written communication, 1963), and all the samples that contained uraninite were collected above the ground-water table. Most were collected within only a few tens of feet beneath the outcrop. The presence of uraninite in the Jackpile, therefore, could be related to proximity to partly oxidized coffinite, as it seems to be in the Westwater Canyon deposits.

The vanadium content of the Jackpile ore is not particularly high, and most of the low-valent vanadium may be present in vanadium-bearing clay and roscoelite. Vanadium-bearing mica was found in veinlets that cut strongly mineralized silicified logs in the Jackpile deposit. Sincosite and paramontroseite (?) were reportedly (Gruner and Knox, 1957) identified in the Jackpile mine, but no details concerning the occurrence are available. The vanadium content of ore in the Woodrow mine is unusually low, and no vanadium minerals have been recognized.

Sulfide minerals are present in all the unoxidized deposits, particularly in the Woodrow deposit. Pyrite is generally most abundant, but marcasite concentrations have been noted. Trace amounts of galena have been found in both the Woodrow and Jackpile deposits.

The Woodrow deposit is apparently unique among deposits in the Grants mineral belt in that it contains copper, zinc, and cobalt sulfide minerals. R. H. Moench (oral communication, 1963) emphasizes, however, that these minerals are highly

Table 4.--Authigenic minerals in deposits in the Jackpile sandstone (of economic usage)

| | Gruner and Smith, 1955 | Weeks, 1956a | Knox and Gruner, 1957 | Moench and Schlee, 1957 | Hilpert and Moench, 1960 | Moench, 1962 | Moench, written communication, 1963 |
|---|---|---|---|---|---|---|---|
| Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$ | | | X | | | X | X |
| Uraninite, $UO_2$ | | | | | | | X |
| Tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}8H_2O$ | | X | X | | | | |
| Metatyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$ | | X | X | | | | |
| Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$ | | | X | | | | |
| Zippeite, $2UO_3 \cdot SO_3 \cdot 5H_2O$ | | X | | | | | |
| Zippeite-like | | X | | | | | X |
| Uranopilite, $(UO_2)_6(SO_4)(OH)_{10} \cdot 12H_2O$ | | X | | | | | X |
| Uranophane, $Ca(UO_2)_2SiO_3(OH)_2 \cdot 5H_2O$ | X | | X | | | | |
| Autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 10\text{-}12H_2O$ | | | | | | | X |
| Meta-autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 8H_2O$ | X | X | X | | | | X |
| Cuprosklodowskite, $Cu(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$ | | | | | | | X |
| Phosphuranylite, $Ca(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$ | | X | | | | | |
| Soddyite, $(UO_2)_5(SiO_4)_2(OH)_2 \cdot 5H_2O$ | X | | X | | | | |
| Paramontroseite, $V_2O_4$ | | | ? | | | | |
| Sincosite, $CaO \cdot V_2O_4 \cdot P_2O_5 \cdot 5H_2O$ | | | X | | | | |
| Pyrite, $FeS_2$ | | | | X | | X | X |
| Marcasite, $FeS_2$ | X | | | X | | | X |
| Chalcopyrite, $CuFeS$ | | | | X | | X | X |
| Covellite, $CuS$ | | | | | | | X |
| Galena, $PbS$ | | | | X | | X | X |
| Sphalerite, $ZnS$ | | | | X | | | |
| Cobaltite, $CoAsS$ | | | | | | X | X |
| Wurtzite, $ZnS$ | | | | | | X | X |
| Barite, $BaSO_4$ | | | | | | X | |
| Calcite, $CaCO_3$ | | | | X | | | |
| Dolomite, $(Ca,Mg)CO_3$ | | | | X | | | |

localized and that they do not markedly distinguish the Woodrow deposit from other deposits in the Jackpile sandstone.

Chalcopyrite is a common associate of coffinite in the Woodrow pipe deposit and locally occurs as minute blebs in wurtzite. Covellite, apparently altered from chalcopyrite, has been noted. Wurtzite was tentatively identified in a polished section of sulfide-bearing ore, and cobaltite, associated with pyrite, was found in two polished sections of the ore.

### OXIDIZED ENVIRONMENT

Most of the uranium deposits in the Jackpile sandstone (of economic usage) are well above the ground-water table and are oxidized to some extent. Most of the oxidized minerals are premining minerals. Postmining minerals are not so common in open-pit operations, such as the Jackpile mine, as they are in underground mines.

The oxidized mineral assemblage in the Jackpile mine is very similar to the assemblages in the near-surface Westwater Canyon deposits near Grants. The most prevalent uranium minerals are vanadates, but phosphates and silicates have been recognized.

Tyuyamunite and metatyuyamunite form small concretionary masses and tabular deposits in the sandstone near the main Jackpile ore body, and presumably they were derived during weathering of the primary ores (Moench, written communication, 1963). Tyuyamunite is also disseminated in partly oxidized primary ore bodies and occupies fractures in silicified fossil logs, mudstone, and diabase dikes, which locally intrude the Jackpile deposit.

Autunite and meta-autunite occur in joints and fractures in mudstone, diabase, and silicified fossil logs. Phosphuranylite, identified by J. R. Houston and reported by A. D. Weeks ( 1956a), occupies joints in silicified fossil logs (Moench, written communication, 1963).

Uranium silicates have been found in minor amounts in the Jackpile mine. Uranophane was reported from the Jackpile (Gruner and Knox) and Windwhip (Gruner and Smith, 1955) deposits. Moench (written communication, 1963) states that uranophane is locally abundant in longitudinal joints in the chilled borders of diabase sills near and in ore bodies.

Soddyite was identified (Gruner and Smith) in the Jackpile mine very close to, if not in contact with, an intrusive diabase sill. Gruner and Smith believe that this is the first occurrence of soddyite known n sedimentary rocks, but they also note that the occurrence is close to an intrusive igneous rock.

In the Woodrow deposit, oxidized uranium minerals are common down to the ground-water table, about 10o feet below the surface. Although minor amounts of efflorescent minerals may have formed on the mine walls, the following discussed mineral seemingly formed in the zone of oxidation before mining was started. Zippeite and zippeite-like minerals (Moench, written communication, 1963) are the most abundant oxidation products in the typical high-grade ore, but lesser amounts of uranopilite are also present. Sparse cuprosklodowskite indicates the anomalously high copper content of the Woodrow ore. Weeks ( 1956a) and Moench have also noted meta-autunite in fractures and partings in fossil bone in the Woodrow mine. Near the outcrop, fluorescent, uranium-bearing opal cements much of the sandstone.

## DEPOSITS IN THE TODILTO LIMESTONE

### UNOXIDIZED ENVIRONMENT

The primary uranium deposits in Todilto Limestone are largely confined to the axial zones of minor anticlines which affect the Todilto but die out in the underlying rocks. Deposits which extend into the base of the overlying Summerville Formation or the top of the underlying Entrada Sandstone are herein considered as deposits in Todilto Limestone.

Among the essentially unoxidized minerals which have been identified are uraninite (pitchblende), coffinite, paramontroseite, haggite, fluorite, pyrite, marcasite, and galena. Occurring with the unoxidized minerals, and perhaps of primary origin, are barite, hematite, and a vanadium clay. Fluorite, in some deposits, is a mineral that particularly distinguishes the authigenic mineral assemblage of these deposits from the deposits in the Morrison and Dakota Formations.

Uraninite (pitchblende var.) was first identified by J. W. Gruner (Rapaport, 1952) and has been reported by nearly all the investigators of the Todilto deposits (table 5). The nonfluoritic ores contain colloform and finely granular uraninite which starts along grain boundaries and veinlets in the limestone and ultimately replaces the limestone grains and veinlet walls. The fluoritic ores contain fine-grained uraninite closely associated with the fluorite. Evidence is conflicting as to whether or not the two are intergrown (Laverty and Gross, 1956; Truesdell and Weeks, 196o).

Truesdell and Weeks show that uraninite is paragenetically later than most low-valent vanadium minerals, fluorite, and some of the pyrite, which it strongly corrodes. Uraninite is about contemporaneous with minute galena cubes and is mostly earlier than coffinite, pyrite, marcasite, barite, and specular hematite.

Coffinite is in relatively minor quantities in comparison to uraninite and was not recognized by the earlier investigators. It evidently has not been observed in ores that contain fluorite. Truesdell and Weeks noted that coffinite coated and replaced uraninite along shrinkage cracks and grain boundaries.

Haggite, paramontroseite, and a vanadium clay largely preceded uraninite deposition. Haggite was deposited as fine blades and fibers along the margins of solution channels and along grain boundaries in the limestone. Some haggite is partly intergrown with, or replaces, paramontroseite as crystalline rosettes and blades. The vanadium clay, in some places, forms nearly spherical aggregates that enclose pyrite or organic matter. A little late haggite, generally closely associated with the earlier haggite, seems to have been deposited after uraninite.

Grantsite is a newly described vanadium-bearing mineral of the intermediate or "corvusite" stage of oxidation (Weeks, Lindberg, and Meyrowitz, 1961). It typically forms clusters of soft, dark olive-green to greenish black fibers and blades with pearly to subadamantine luster. Grantsite was originally found as fibrous aggregates on fracture surfaces at The Anaconda Company's F-33 mine.

Fluorite is present in only a few of the Todilto deposits and absent in deposits that contain appreciable amounts of

Table 5.--Authigenic minerals in deposits in the Todilto Limestone

| | Gruner, Towle, Gardiner, 1951 | Towle and Rapaport, 1952 | Rapaport, 1952 | Gruner, Gardiner, Smith, 1954 | Laverty and Gross, 1956 | Gabelman, 1956a | Hilpert and Corey, 1955 | Sun and Weber, 1955 | Weeks, 1956a | Weeks, 1956b | Weeks and Truesdell, 1958a | Weeks and Truesdell, 1958b | Sun and Weber, 1958 | Moench and Schlee, 1959 | Thaden and Santos, 1959 | Truesdell and Weeks, 1960 | Weeks, Lindberg, Meyrowitz, 1961 | Moench, written communication, 1963 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Uraninite, $UO_2$ | X | X | X | X | X | X | X | | | X | X | X | | X | X | X | | X |
| Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$ | | | | | X | | ? | | | | X | X | | X | X | X | | X |
| Gummite | | | ? | | | X | | | | | | | | | | | | |
| Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$ | X | X | X | X | X | X | X | | | | | | | | | | | X |
| Tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}8H_2O$ | X | X | X | X | X | X | X | | X | | | X | | | X | | | X |
| Metatyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$ | | | | X | | X | | | X | | | | | | | | | X |
| Uranophane, $Ca(UO_2)_2SiO_3(OH)_2 \cdot 5H_2O$ | X | X | X | X | X | X | X | | X | | X | X | | | X | | | |
| Beta-uranotile, $Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$ | | | X | X | X | X | | | | | | | | | | | | |
| Liebigite, $Ca_2(UO_2)(CO_3)_3 \cdot 10H_2O$ | | | | | | | | | X | | | | | | | | | |
| Sklodowskite, $Mg(UO_2)_2(SiO_3)_2(OH)_2 \cdot 6H_2O$ | | | ? | | | X | | | | | | | | | | | | |
| Cuprosklodowskite, $Cu(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$ | | | | | | | | X | | | | | X | | | | | |
| Paramontroseite, $V_2O_4$ | | | | | | | | | | | X | X | | | X | X | | |
| Haggite, $V_2O_3 \cdot V_2O_4 \cdot 3H_2O$ | | | | | | | | | | | X | X | | | X | X | | |
| V-clay | | | | | X | | | | | | | | | | | X | | X |
| Grantsite, $2Na_2O \cdot CaO \cdot V_2O_4 \cdot 5V_2O_5 \cdot 8H_2O$ | | | | | | | | | | | | | | | | | X | |
| Santafeite, $Na_2O \cdot 3MnO_2 \cdot 6(Mn,Ca,Sr)O \cdot 3(V_1As)_2O_5 \cdot 8H_2O$ | | | | | | | | | | | | | X | | | | | |
| Ardennite[1/] | | | | | | | | 1/ | | | | | | | | | | |
| Hewettite, $CaV_6O_{16} \cdot 9H_2O$ | | | | | | | | | | | X | | | | X | | | |
| Pascoite, $Ca_3V_{10}O_{28} \cdot 16H_2O$ | | | | | | | | | | | X | | | | | | | |
| Fluorite, $CaF_2$ | X | X | X | X | X | X | X | | X | | | X | | | X | X | | |
| Pyrite, $FeS_2$ | | X | X | X | X | X | X | | | | X | X | | | X | X | | |
| Marcasite, $FeS_2$ | | | | X | | | | | | | | | | | | X | | |
| Galena, PbS | | | | X | | | | | | X | X | X | | | | X | | X |
| Chalcopyrite, $CuFeS_2$ | | | | | | | | | | | | | | | | | | X |
| Barite, $BaSO_4$ | | X | X | | X | X | X | | X | | X | X | | | X | X | | |
| Cryptomelane, $K_2O \cdot MnO \cdot 8MnO_2 \cdot 2H_2O$ | | | X | | | | | | | | | | | | | | | |
| Psilomelane, $H_4Mn_2Mn_8O_{20}$ | | | X | X | X | | | | | | | | | | | | | |
| Manganese oxides | | | | | | X | | | | | | | | | | | | |
| Hematite, $Fe_2O_3$ | | X | X | | X | X | | | | | | | | | X | X | | |

1/ A new mineral, later named santafeite, was misidentified as ardennite by Sun and Weber (1955).

coffinite, vanadium minerals, or early pyrite (Laverty and Gross). Where present, most of the fluorite was emplaced before the uranium minerals but following a partial recrystallization of the limestone. Fluorite completely replaced some susceptible layers in the limestone and partly replaced others. Most of the fluorite is fine-grained and dark purple, but some is clear (Rapaport).

Galena, pyrite, and marcasite are the only sulfide minerals recognized in the Todilto deposits. Fine-grained cubes of galena were deposited during and after uraninite and coffinite, and replace early pyrite and haggite. Early pyrite is corroded and replaced by other minerals, whereas the more prevalent late pyrite occurs in solution cavities and fractures or as a partial replacement of detrital grains such as quartz. All marcasite seems to be late.

Calcite of the limestone is extensively recrystallized along fractures, bedding planes, and solution cavities in and near ore deposits. Coarser-grained calcite formed at several periods and is both earlier and later than most other minerals. Any fractured, early-formed mineral is likely to be filled, and even partly replaced, by calcite.

Fine-grained red hematite is common in uraninite-bearing zones, and Truesdell and Weeks noted specular hematite associated with vanadium clay in some specimens. Hematite pseudormorphs after pyrite are present in oxidized parts of the deposits (Laverty and Gross).

Barite is associated with the unoxidized minerals (Laverty and Gross; Truesdell and Weeks). Rapaport believed that blades and clusters of clove-brown resinous barite, found chiefly in veinlets but also disseminated in the host rocks, is perhaps the most characteristic accessory mineral in the ore.

### OXIDIZED ENVIRONMENT

Many of the Todilto deposits are either exposed at the outcrop, overlain by alluvium and eluvium, or are overlain by only a few feet of Summerville Formation. Oxidized minerals, therefore, are the dominant minerals found in many of the near-surface deposits. Since these are mostly premining minerals, yet have not moved any great distance under weathering conditions, it is obvious that they are relatively insoluble in normal meteoric and ground waters.

The descriptions of Todilto ores commonly list the oxidized minerals, but there are few detailed accounts of the mineral occurrences. It is known, however, that most of the oxidized minerals fill or coat the walls of fractures and bedding plane joints, and occupy solution cavities associated with coarse-grained calcite.

Santafeite, a black vanadate containing appreciable manganese, was found near Grants in 1951 and named in 1958 (Sun and Weber, 1958). It occurs as a very brittle subadamantine mineral intergrown with calcite and forms small rosettes of acicular crystals on joint surfaces at the outcrop of the Todilto near Grants. It had previously (Sun and Weber, 1955) been incorrectly identified as ardennite.

Carnotite was noted as a common secondary mineral in the Todilto deposits by nearly all investigators up to 1956; after that it was rarely mentioned. Although small amounts of carnotite are probably present, tyuyamunite and metatyuyamunite, which are quite common in the deposits, are much more likely to form in an environment with abundant calcite than in carnotite.

Sklodowskite and gummite were tentatively identified by J. W. Gruner and reported by Rapaport; Gabelman later reported the presence of sklodowskite crediting the reference to R. A. Laverty. Sparse cuprosklodowskite crystals are reportedly (Sun and Weber, 1955, 1958) present on some of the santafeite crystals. This is the only copper-bearing mineral known in any of the Todilto, Morrison, or Dakota deposits, except in the Woodrow pipe at Laguna.

Uranophane is described by Rapaport as being the most common uranium silicate in the deposits. It occurs in vugs and open fractures as bundles and rosettes of bright yellow acicular crystals as much as 0.5 inch long. Beta-uranotile is also present but is reported to be quite rare.

Liebigite was noted by Weeks (1956a), but she provided no details and very likely it was collected from a mine wall.

Various oxides containing manganese, in addition to santafeite, have been noted in the deposits. Some are reported merely as manganese oxides, but J. W. Gruner (Rapaport) identified black films and dendrites of psilomelane and cryptomelane on fracture surfaces.

## DEPOSITS IN THE DAKOTA SANDSTONE

Data on the authigenic mineralogy (table 6) of the uranium deposits in the Dakota Sandstone are very few, and descriptions of the occurrences are generally not recorded or lack detail. Either primary unoxidized uranium minerals are quite rare or no concerted effort was made to isolate and identify them, since most geologists who have studied the deposits do not refer to them.

The ore bodies occur either in carbonaceous shales in the lower part of the Dakota Sandstone or in the closely associated sandstone lenses. Most of the secondary minerals are found in the sandstones, and there is some indication that they were derived, in places, by weathering of the enclosing shales.

Uraninite, reportedly (Gabelman, 1956a), was abundant in two ore bodies in sandstone below the oxidized zone at the Diamond No. **a** mine a few miles southeast of Gallup. Gabelman stated, however, that no primary uranium minerals are visible where the uranium occurs in shale or peat, and it is presumed that the uranium is adsorbed by the carbon in these materials.

Among the secondary uranium minerals identified in deposits in the Dakota, carnotite and tyuyamunite-metatyuyamunite seem to be the most abundant. These occur generally as impregnations and joint fillings in the ore-bearing sandstones, particularly near accumulations of carbonaceous trash (Gabelman, 1956a). Meta-autunite and a variety of uranophane have also been identified at the "Desanti" (probably Becenti) mine (Gruner, Gardiner, and Smith), but details of the occurrence are lacking. Associated with the secondary uranium minerals are abundant limonite—both as disseminations and fracture fillings—and gypsum, jarosite, and calcite.

The first level in the Church Rock mine near Gallup reportedly is developed in the Dakota Sandstone. The thickness and character of the host sandstone suggest that it occurs in a channel incised in the Brushy Basin Member of the Morrison Formation, and, as such, it resembles the Jackpile sandstone. Pascoite, red native selenium (?), and a zippeite-like mineral (Frondel, p. 146) have been recognized on the walls of the workings at this level, and, if they are in the Dakota Sandstone, should be noted here.

Table 6.--Authigenic minerals in deposits in the Dakota Sandstone

| | Mirskey, 1953 | Gruner, Gardiner, Smith, 1954 | Gabelman, 1956a | Hilpert and Corey, 1955 | Weeks and Truesdell, 1958b | Thaden and Santos, 1959 |
|---|---|---|---|---|---|---|
| Uraninite, $UO_2$ | | | X | | | X |
| U adsorbed on carbon | | | X | | | |
| Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$ | | | X | X | X | X |
| Tyuyamunite, $Ca(UO_2)_2(V_2O_4)_2 \cdot 5\text{-}8H_2O$ | | | X | X | | X |
| Metatyuyamunite, $Ca(UO_2)_2(V_2O_4)_2 \cdot 3\text{-}5H_2O$ | ? | X | | | | |
| Uranophane, $Ca(UO_2)_2SiO_3(OH)_2 \cdot 5H_2O$ | | X | | | | |
| Meta-autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 8H_2O$ | | X | | | | |
| Pyrite, $FeS_2$ | | | | X | | |
| Limonite, $Fe_2O_3 \cdot XH_2O$ | | | X | X | | |
| Gypsum, $CaSO_4 \cdot 2H_2O$ | | | X | | | |
| Jarosite, $KFe_3(SO_4)_2(OH)_6$ | | | X | | | |
| Calcite, $CaCO_3$ | | | X | | | |

## SUMMARY

As stated in the introduction, there is considerable diversity among the mineral assemblages from deposit to deposit in the Grants mineral belt. There is also, however, an overriding similarity among all the deposits, and it may be more informative, in summary, to consider these similarities than the differences.

Primary unoxidized uranium in all the deposits occurs principally as either coffinite or uraninite associated with pyrite and generally with some type of organic material. Other minerals that may or may not be present include montroseite, fluorite, jordisite, and base-metal sulfides.

Oxidation of these primary minerals before mining and in an environment with a low vanadium content can result in the formation of uranium silicates or phosphates such as uranophane and autunite. In such an environment, however, it may be more common for most of the uranium to be leached from the rocks.

If abundant vanadium is present under oxidizing conditions, the uranium enters into uranium vanadate minerals, such as carnotite and tyuyamunite, of low solubility. The excess vanadium or uranium is probably leached out of the system.

In the oxidizing environment, such minerals as native selenium, barite, calcite, gypsum, and cryptomelane may also be formed.

After mining is commenced, oxidation is locally rapid, and the ground-water and capillary solutions are likely to contain at least local concentrations of such metals as uranium, vanadium, molybdenum, sodium, calcium, and iron with sulfate, carbonate, and bicarbonate anions. These form a large variety of evaporite or efflorescent minerals on the mine walls. Among them, andersonite, zippeite, thenardite, pascoite, and ilsemannite are probably the most common.

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# *Alteration of Morrison Sandstone*

S. RALPH AUSTIN

## ABSTRACT

The upper Morrison sandstone host rocks of the uranium deposits near Ambrosia Lake are universally altered. Alteration under reducing conditions produced kaolinite, chlorite (?), pyrite, marcasite, anatase, calcite cement, quartz overgrowths, authigenic feldspar, and partly dissolved detrital feldspar. Hollow shells are remnants of sanidine. The sediment originally contained more feldspar, limestone, volcanics, and detrital heavy minerals than now. Supersedure of feldspar, magnetite, and ilmenite by kaolinite, pyrite, and titanic indicates alteration under acid conditions. This parallels the alteration sequence in kaolinite zones of hydrothermal veins and suggests similar altering fluids, which may nevertheless have a different origin. Ambiguous mineral sequences suggest penecontemporaneity of alteration and ore. Silica released by alteration may have combined with uranium to form coffinite. Superposition of alteration and ore, if unrelated, would seem extremely fortuitous.

## INTRODUCTION

This paper summarizes an uncompleted study of the alteration of the Morrison sandstone host rocks of uranium deposits centered around Ambrosia Lake. Ambrosia Lake, about 20 miles north of Grants, New Mexico (fig. r), is the focal point of an area of uranium production extending from the Jackpile mine on the east nearly to Gallup at the west. The largest known deposits are in the Westwater Canyon, Poison Canyon, "Jackpile," and other sandstone units in the upper part of the Morrison Formation.

These host rocks are coarse-grained, poorly sorted, feldspathic to arkosic sandstone containing abundant mudstone pellets, pebbles and cobbles. Mudstone lenses and splits form local, more or less impermeable barriers to movement of fluids. Organic debris is rather abundant in some places.

Uranium, principally as coffinite, is commonly associated with brown or black organic material occuring as grain coatings and small pellets. The nature and origin of this organic material is a subject of much controversy and will not be discussed here.

Vanadium is commonly less concentrated but far more widespread in low concentrations than is uranium. Among other elements concentrated in and near ore bodies are molybdenum as jordisite and ilsemannite, and selenium as ferroselite (iron selenide) and as both the red and gray forms of native selenium.

Alteration effects to be discussed here do not include the formation of ore bodies, but rather some of the other changes

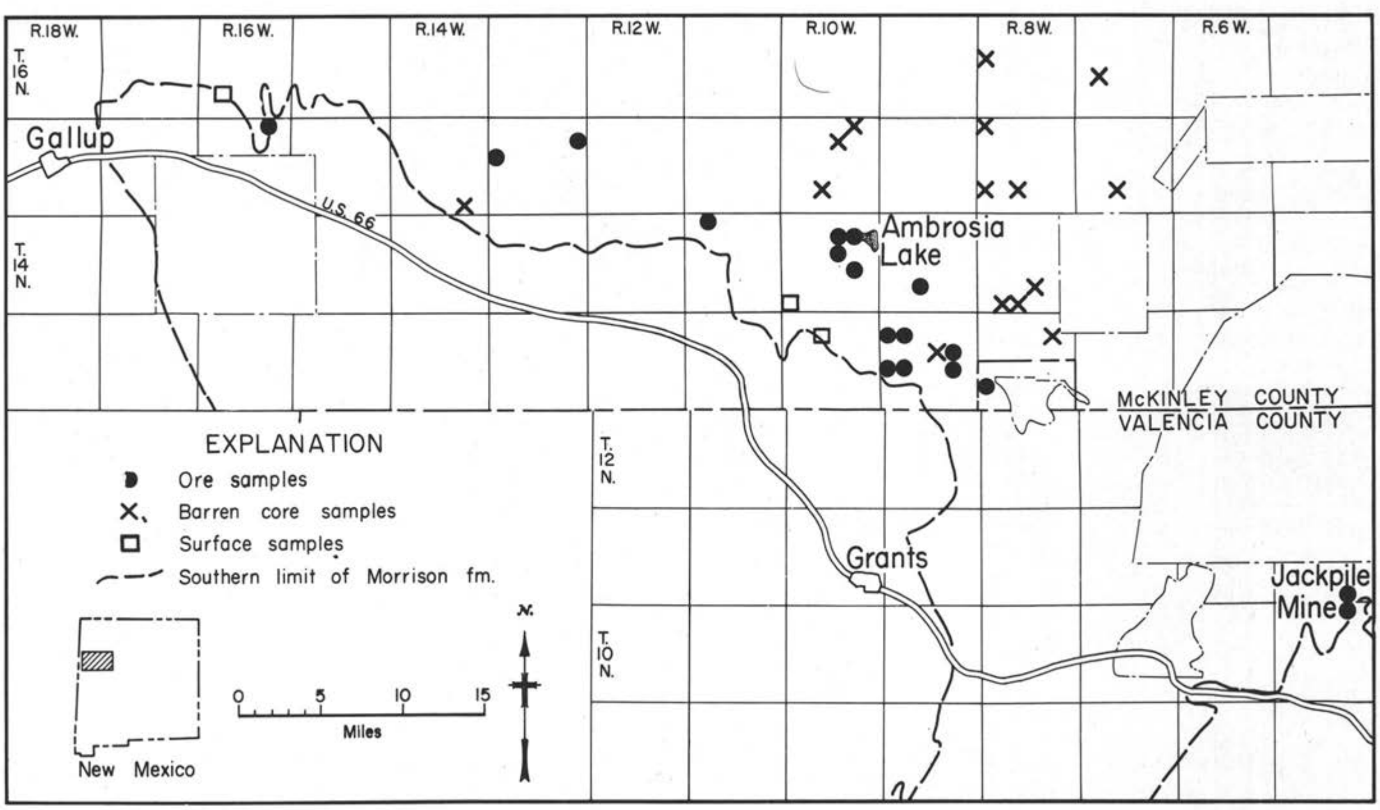


Figure 1

Location of land sections sampled, McKinley and Valencia Counties, N. Mex.

that the host rocks have undergone since deposition. These alteration effects are evident not only in and near ore but in every sample collected, even several miles from known ore. In Figure I, round black dots indicate sections from which subsurface ore samples were taken, "x" indicates barren core samples, and hollow squares indicate surface samples. The preponderance of samples studied for this paper is from the Ambrosia Lake area of the Grants district. Although a few samples are from the Gallup and Laguna districts, the term *Ambrosia Lake* is used in most instances in the text.

# ALTERATION

## PROCESS

At least two periods of alteration are evident in these sandstones: an early one under reducing conditions and a later one under oxidizing conditions. Unoxidized or slightly oxidized zones are gray, greenish gray, dark brown, or black; whereas oxidized zones are yellow, limonite brown, or red (fig. z). Ore is largely confined to the unoxidized zones; therefore, this discussion will pertain chiefly to alteration that appears to have taken place under reducing conditions. Nevertheless, many of the earlier alteration effects are still discernible after oxidation.

Alteration products include kaolinite, chlorite (?), pyrite and marcasite, anatase (titanium dioxide), calcite cement, quartz overgrowths, authigenic feldspar, and partly dissolved detrital feldspar.

Perhaps the most conspicuous and distinctive alteration products are white kaolinite "nests" (fig. 3). These are entirely distinct from the greenish gray detrital mudstone pellets, which according to Knox and Gruner (1957) are probably a mixture of montmorillonite and illite. Each of the abundant kaolinite "nests" or "flowers" may enclose many detrital grains; they do not represent feldspar grains altered in *situ*. Rather, silicon and aluminum from dissolved feldspar were transported at least short distances and deposited as kaolinite. Much less commonly, kaolinite does actually replace detrital feldspar (fig. 4).

Another authigenic clay mineral, tentatively identified as chlorite, occurs rarely as coatings on detrital grains and is shown in thinsection in Figure 5. It occurs in and near zones tightly cemented by calcite.

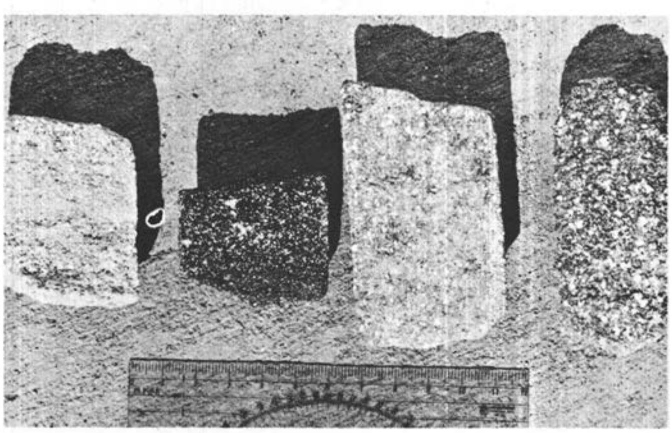

Figure 2

Core sample of (left to right) gray and black, unoxidized, and brown and red, oxidized, sandstones.

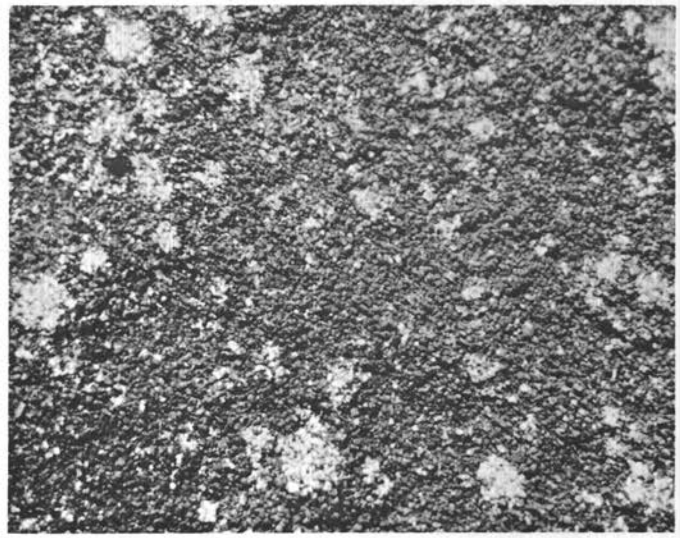

Figure 3

Surface of split sandstone core containing white kaolinite nests, each enclosing many sand grains. About 3×.

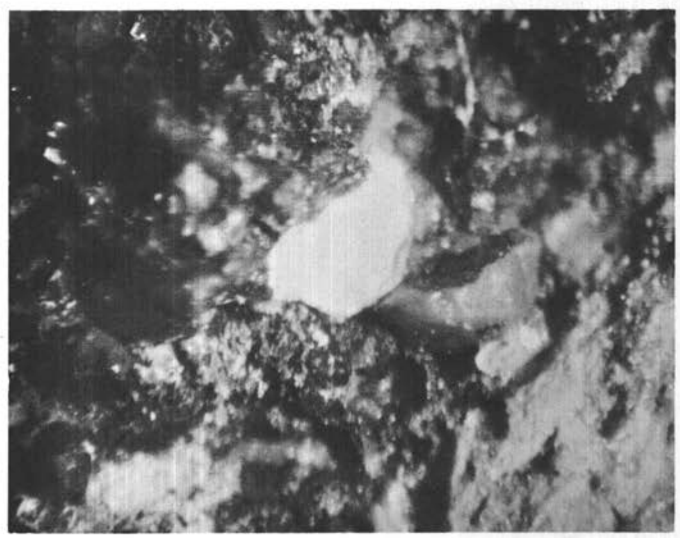

Figure 4

SURFACE OF SPLIT ARGILLACEOUS SANDSTONE CORE

White kaolinite replaces detrital grain. Detrital clay partly coats some grains. Mudstone pellet occupies lower right corner. About 66×.

Authigenic pyrite was observed in nearly every inch of sandstone core and in nearly every hand sample from unoxidized zones. It occurs as euhedral crystals and crystal clusters (fig. 6), also as anhedral masses. These two types probably represent distinct generations. Less commonly, the iron sulfide mineral is marcasite. In and near ore, iron may be combined with selenium to form ferroselite. Pyrite, especially in minute euhedral crystals, appears to be much more abundant in ore, and for at least hundreds or perhaps thousands of feet outside the ore bodies, than several miles from known ore.

Authigenic anatase is perhaps as widespread but not so abundant as pyrite (fig. 7). Since it is stable under oxidizing conditions, it persists in oxidized zones. Hollow, geodelike

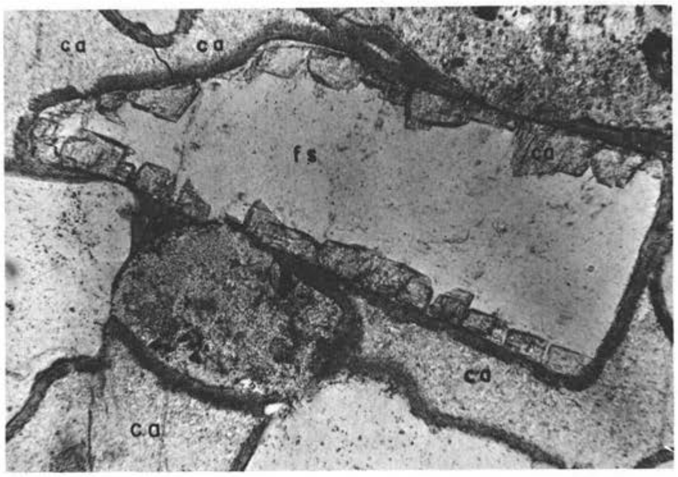


Figure 5

THINSECTION OF SANDSTONE

Chlorite(?) rims detrital grains in calcite (ca) matrix. Calcite, in crystal continuity with matrix, partly replaces feldspar grains (fs). Plain light. About 78×.

Figure 6

Euhedral crystals and crystal clusters of pyrite in sandstone. Cluster is within shell of detrital grain. About 64×.

clusters of anatase and pyrite crystals replace a very few of the detrital grains.

Perhaps the most unusual alteration features are hollow shells which, when perfectly developed, resemble miniature - ping-pong balls (fig. 8). D. N. Miller (1955) identified similar shells from the Permian Pierce Canyon Formation in western Texas and southeastern New Mexico as hollow sanidine grains. Most if not all, the shells here described also result from partial solution of detrital sanidine. Some are completely empty; a few contain authigenic pyrite, anatase, calcite, or secondary uranium minerals; but most contain sliverlike remnants of the original sanidine (fig. 9). These remnants have been identified optically, spectographically (Riley, L. B., Myers, A. T., and Conklin, N. M., written communication, May 25, 1959, USGS Report No. TDS-9435), and by X-ray* as sanidine containing about 3o percent soda feldspar and 70 percent potash feldspar. However, many remnants are so perfectly faceted by solution that they have been previously misidentified as authigenic adularia.

All stages from nearly whole detrital grains to empty shells are present. Figure 10 shows a grain only slightly dissolved with part of the shell protruding over the dissolved portion.

Figure I 1 shows the pressure-solution mechanism believed to have initiated solution. Two small grains are pressed into the sides of the larger sanidine grain. A similar grain was removed from the pit now visible in the larger grain.

Occasionally, castellated remnants are formed (figs. 12 and 13). These show clearly the relationship between the needlelike remnants and grains that are only slightly dissolved.

Grains of other varieties of feldspar are somewhat similarly but less strikingly altered. These grains are whitened but rarely kaolinized. Their interiors consist of an incoherent, powdery aggregate of rodlike feldspar remnants. Microcline, however, seldom shows much alteration.

Authigenic feldspar overgrowths, probably of potash feldspar, also occur. Rarely, the shells described above consist of, or are overgrown by, authigenic feldspar in recognizable crystals. These are shown in thinsection in Figure 14.

Quartz is much less altered than feldspar. However, the grains are commonly slightly etched or pitted, and partial overgrowths of authigenic quartz on detrital grains are abundant in some zones. The quartz grain in Figure 15 shows both a pressure-solution pit and numerous typical overgrowths. However, much of the silica to form overgrowths may have been derived from feldspar rather than quartz.

Calcite cement has developed or has been introduced, especially just above mudstone units. Some ore is sandwiched between calcitic zones, commonly with some interpenetration of ore and calcite. The calcite cement commonly forms large

Figure 7

Sandstone containing detrital grain superseded by anatase (nearly black) and pyrite (two largest brightly reflecting crystals within dark anatase mass). Small euhedral crystals outside grain are also pyrite. About 31×.

* H. C. Granger of USGS assisted in interpretation of X-ray diffractometer pattern.

crystals, each enclosing several detrital grains; the crystals being either discrete or coalescing to form tight calcite cement showing luster mottling (fig. 16).

Of the hundreds of feet of core and hundreds of hand samples examined under the microscope, all showed some degree of postdepositional alteration.

## NATURE OF ORIGINAL SEDIMENT

Detrital grains have been least altered in the most argillaceous sandstone or sandy mudstone lenses and in some zones, tightly cemented by calcite. These zones provide a clue to the original composition of the sandstone.

The feldspar content of the sediment before alteration can only be estimated, but the sediment was undoubtedly a true arkose with 30 percent or more feldspar. A small percentage of the grains is extrusive igneous rock fragments. The sanidine grains also probably indicate an extrusive source for part of the sediment. Finer-grained volcanic debris may have been present but is now altered beyond recognition.

The detrital heavy mineral suite is rather limited. In the present study only garnet, tourmaline, zircon, micas, chlorite, and leucoxene have been identified. Knox and Gruner reported apatite and rutile in addition. No amphiboles nor pyroxenes have been identified. The absence of magnetite and ilmenite is especially noteworthy. Because ilmenite is relatively resistant to weathering, it would be expected in such an immature, arkosic sediment. Dean Webb (oral communication) of the Kermac Nuclear Fuels Corporation has examined the electromagnets in the grinding circuit of the Kermac mill for magnetite and ilmenite but has found neither mineral. However, magnetite and ilmenite and most other iron- and titanium-bearing minerals have been completely superseded, and partly replaced, by pyrite and anatase.

Few, if any, grains of detrital limestone are found in most of the sandstones. However, pellets of detrital limestone are fairly common in some zones that are well cemented with calcite. It seems likely that detrital limestone grains were once equally abundant throughout the sandstones but were preserved only where protected by early calcite cement.

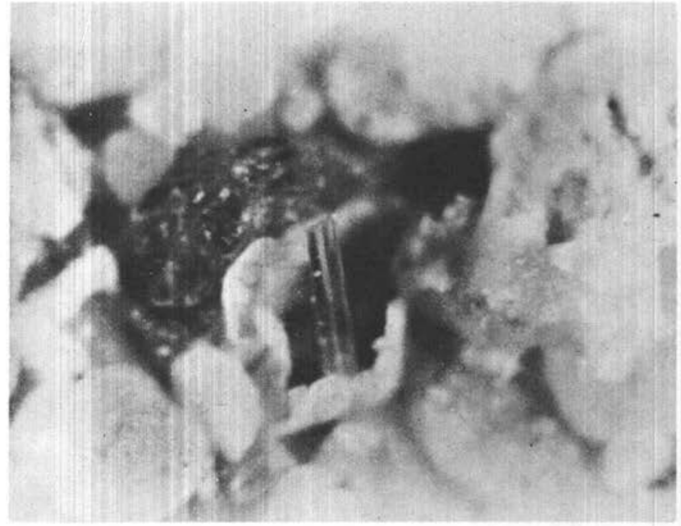

Figure 9

FRACTURED SURFACE OF SANDSTONE

Part of shell of detrital sanidine grain near center broken away to reveal sliverlike remnant. About 28×.

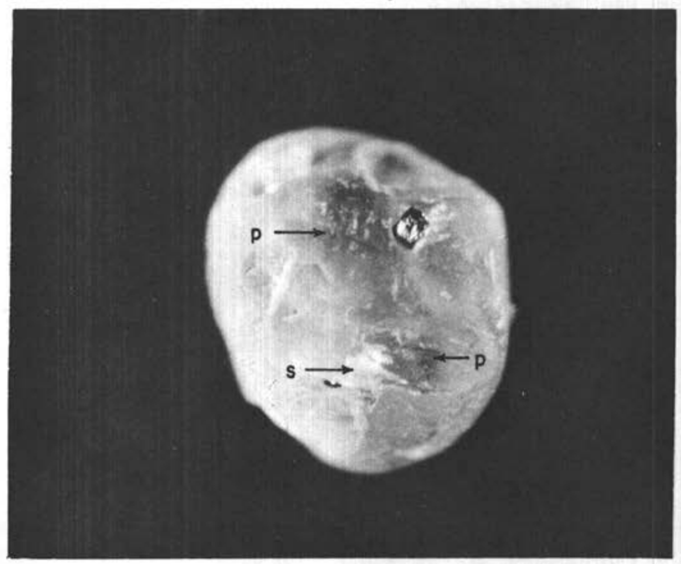


Figure 10

SLIGHTLY DISSOLVED DETRITAL SANIDINE GRAIN

Part of shell (s) protrudes over one of two shallow solution pits (p). Imbedded crystal is cubic pyrite. About 35×.

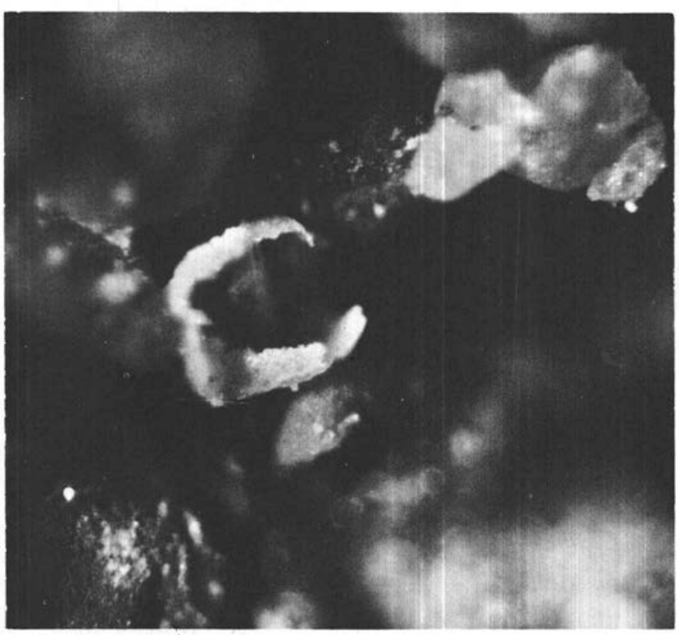

Figure 8

Part of white hollow shell of detrital grain in sandstone. About 80×.

## CHARACTER OF ALTERING FLUIDS

If we assume that all or most of the alteration effects evident in unoxidized zones occurred as part of the same general process, it may be possible to deduce the type of fluids that might produce them.

Grim (1953) summarized work showing that kaolinite

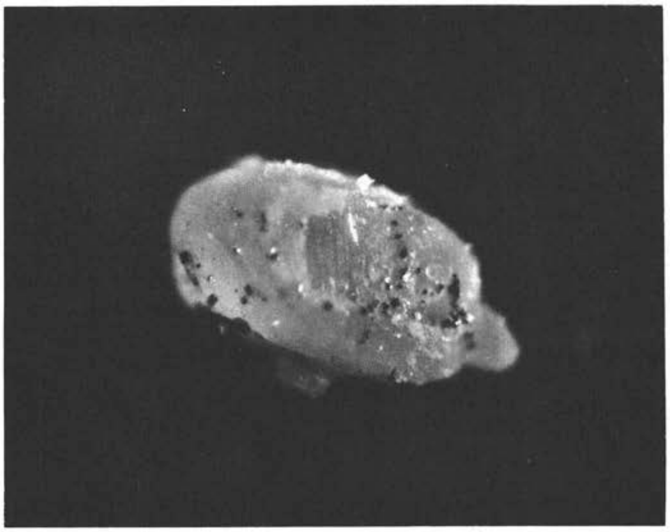

Figure 11

Detrital sanidine grain with smaller grains pressed into sides and pit in top from which similar small grain was removed. Small, dark crystals are pyrite. About 40×.

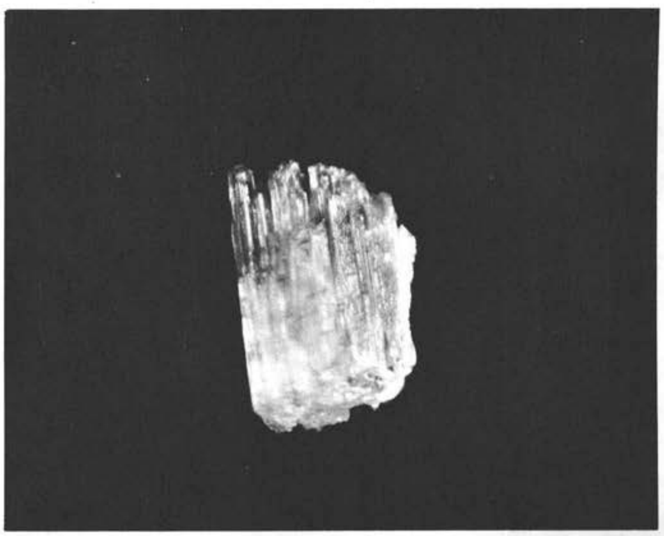

Figure 12

Castellated remnant of detrital sanidine grain. Shell removed during disaggregation of sandstone. About 35×.

formation is favored by acid conditions. In the present instance, however, acid conditions due to surface weathering and any other phenomena occurring under oxidizing conditions are ruled out because the accompanying pyrite will form only under reducing conditions.

Lynd 1960) found alkaline solutions ineffective and sulfuric and humic acid solutions most effective in altering ilmenite at room temperature. The only identifiable alteration product was rutile, which, like anatase, is a polymorph of titania.

Gruner (1959) also produced rutile from ilmenite, using hydrogen sulfide at about 300° C. We might expect similar results at lower temperatures during much longer geologic time.

The supersedure of feldspars by kaolinite and quartz, and of magnetite, ilmenite, and other iron and titanium minerals by pyrite and anatase, seems compatible with alteration under reducing conditions by fluids, including perhaps sulfuric acid, hydrogen sulfide, other sulfur compounds and complexes, and humic acids.

The kaolinite-pyrite-anatase assemblage at Ambrosia Lake closely parallels the kaolinite-pyrite-rutile assemblage for intrusive igneous rocks of some hydrothermal deposits. The supersedure and partial replacement of feldspar, magnetite, and ilmenite in some hydrothermal deposits resembles the alteration at Ambrosia Lake. One might conclude that the fluids responsible for alteration at Ambrosia Lake resembled

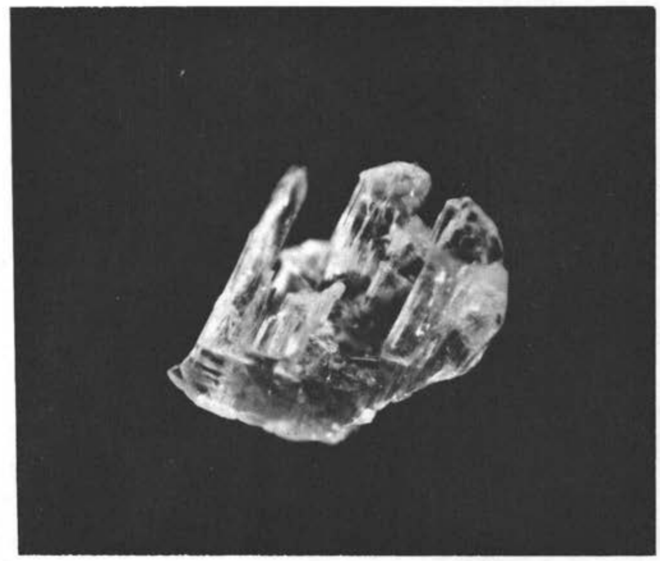

Figure 13

Castellated remnant of detrital sanidine grain. Shell removed during disaggregation of sandstone. About 35×.

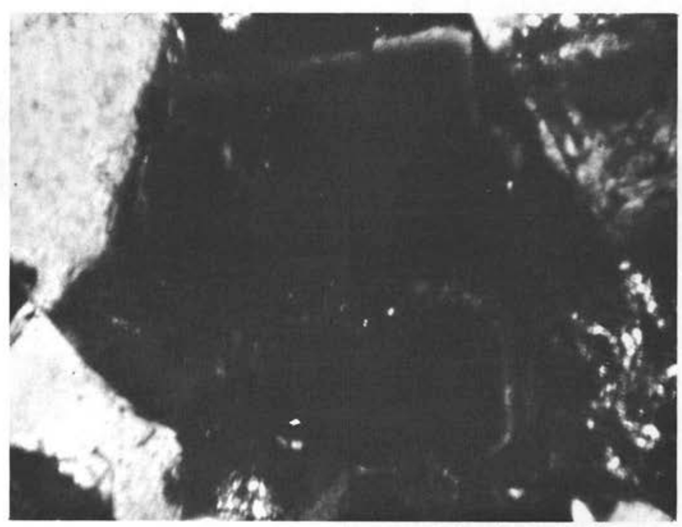

Figure 14

Thinsection of sandstone. Authigenic feldspar overgrowth forms thin partial shell and septum (light gray) within void (black). Original grain has dissolved leaving inner void cut by septum formed by healing of former cleavage. Crossed nicols. About 65×.

hydrothermal fluids in results produced and in composition, if not in temperature. There may, however, be other than hydrothermal origins for such fluids.

The question arises, "What, if any, relationship does this alteration bear to uranium deposition?" Certainly, fluids capable of attacking quartz, feldspar, magnetite, ilmenite, and other detrital minerals, and of depositing some of their constituents in a new suite of minerals, should be considered as possible instruments in forming uranium deposits.

It is commonly conceded that alteration is related to mineralization in hydrothermal veins and porphyry copper deposits. Wright and Bieler (1960) described alteration associated with uranium-bearing veins in the Boulder batholith, Montana, where, as at Ambrosia Lake, kaolinite is a conspicuous alteration product. In the laboratory it has been

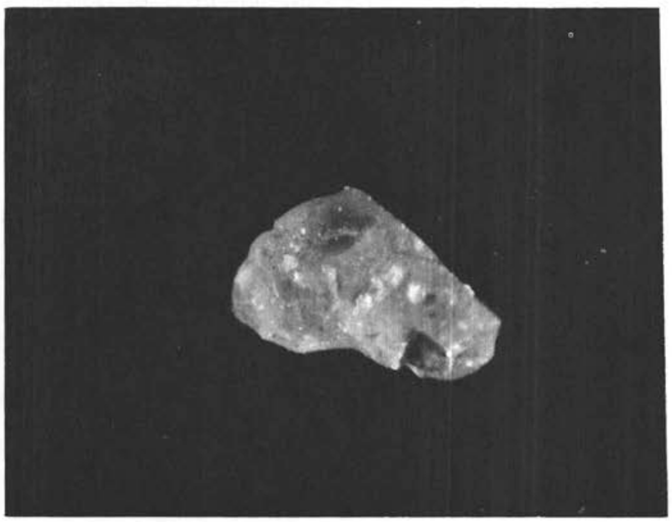

Figure 15

Quartz grain with solution pit (lower right) and numerous authigenic quartz overgrowths. About 20×.

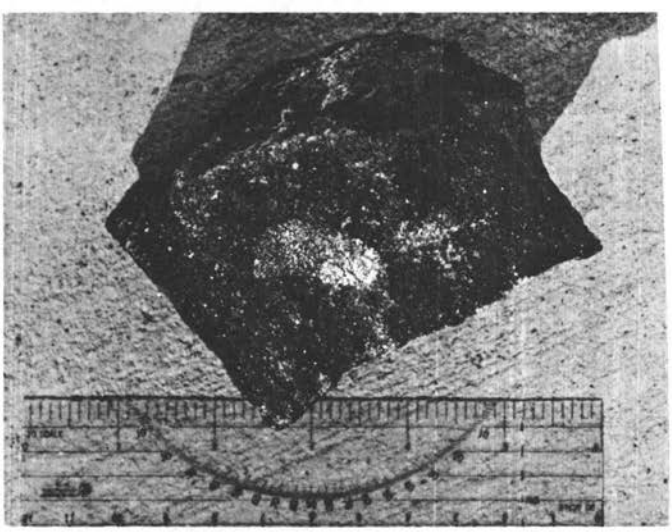

Figure 16

Calcitic sandstone ore specimen showing luster mottling. Reflections from cleavages of two differently oriented crystals of calcite cement produce adjacent light gray and nearly white areas near center.

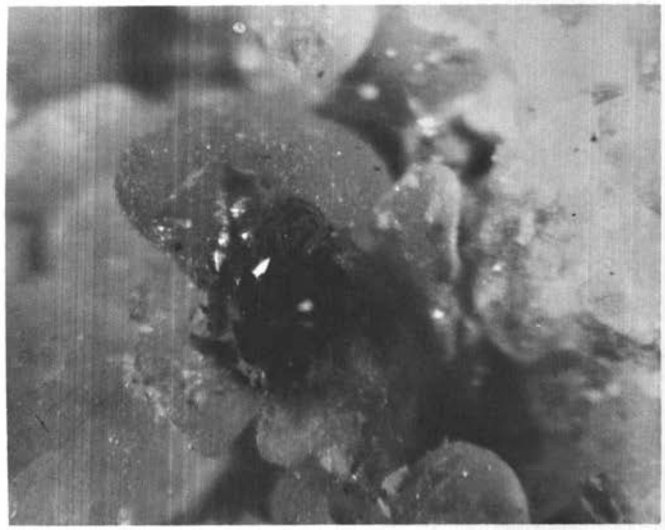

Figure 17

Black pellet of organic material on broken surface of sandstone. Adjacent large quartz grain has authigenic overgrowths partly covered by organic material.

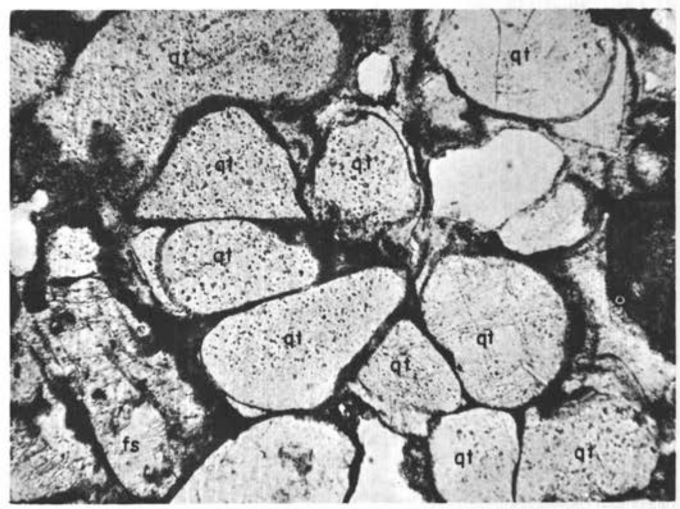


Figure 18

Thinsection of sandstone with detrital quartz gains (qt) coated with organic material, partly overgrown by authigenic quartz. One feldspar grain (fs). Clear white areas are holes in section. About 65×.

demonstrated that the acid solutions postulated here can both carry uranium and also precipitate it from alkaline solutions.

## PARAGENESIS

It has been argued that alteration at Ambrosia Lake greatly antedated mineralization. On the other hand, kaolinite is not commonly stained by the uranium-bearing organic material; thus, kaolinite seems to be later.

It is difficult to determine paragenetic relations and mineral sequences in any poorly consolidated sandstone containing delicate features easily destroyed by sectioning. At Ambrosia Lake there is the added fact that the ore mineral coffinite is positively identifiable only by X-ray and is not commonly recognizable under the microscope. However, the time of mineral alteration as related to deposition or redistribution of the organic material in which the coffinite occurs can sometimes be determined. For example, Figure 17 shows a pellet of organic matter adjacent to a quartz overgrowth. Some of the organic matter coats the overgrowth and must have been emplaced after the overgrowth was formed. Much more commonly, however, quartz overgrowths cover organic coatings, as shown in thinsection in Figure 18.

In general, there is more evidence that organic coatings preceded alteration than the contrary. Nevertheless, the conflicting evidence can perhaps best be reconciled by considering that the organic coatings are penecontemporaneous or overlapping in time with the alteration; sometimes they appear earlier, sometimes later. This does not prove even the temporal relationship of uranium deposition to alteration. Nevertheless, both the solution of detrital feldspar and the authigenic quartz and feldspar overgrowths, all of which may have occurred simultaneously, indicate periods when abundant silica must have been available for the formation of the uranium ore mineral coffinite.

Sizeable uranium deposits are a geologic rarity. Widespread alteration of the type described here appears to be almost equally rare (van Andel, 1959, and written communication). Either, by some even more rare coincidence, alteration and mineralization are superimposed at Ambrosia Lake or the alteration is related to uranium deposition.

## SUMMARY

The sandstones of the Morrison Formation in the Grants-Gallup—Laguna area are universally altered, not only in and near ore but wherever sampled, even several miles from known ore. The sandstones were originally arkosic and contained a suite of unstable heavy minerals, now vanished, and more fragments of extrusixe igneous rocks and limestone than at present.

The altering fluids probably contained sulfuric acid, hydrogen sulfide, or other sulfur compounds, and humic acids. Alteration has produced empty shells of detrital grains and a suite of authigenic minerals, thus: (r) empty shells result from solution of detrital sanidine; (2) kaolinite supersedes, but rarely replaces, feldspars; (3) authigenic feldspar occurs as overgrowths; (4) excess silica forms quartz overgrowths; (5) pyrite and anatase entirely supersede and partially replace magnetite and ilmenite; and (6) coarsely crystalline calcite cement has probably been formed mostly by redistribution from detrital limestone pellets. Mineralogically, the alteration strikingly parallels that found in the kaolinite zone of some hydrothermal deposits, but this does not necessarily indicate a hydrothermal origin.

Although the relation of alteration to uranium mineralization is rather obscure, it seems that (1) conflicting evidence of age relationships may indicate that the two are penecontemporaneous or overlapping; (2) pyritization appears to be more intense in and near ore than hundreds or thousands of feet distant; (3) alteration released abundant silica that could have combined with uranium to form the ore mineral coffinite; (4) similar alteration around hydrothermal vein deposits is accepted without question as being related to mineralization; and (5) either the alteration is related to uranium deposition or there has been an unusual superposition of two rather rare and unrelated phenomena.

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# *Geology of the Black Jack No. 1 Mine, Smith Lake Area*

M. E. MACRAE

## ABSTRACT

The Black Jack No. i ore body is on the southern rim of the San Juan Basin in the upper half of the Westwater Canyon Member of the (Jurassic) Morrison Formation.

The depositional environment is a continental, variably sorted, fine- *b* very coarse-grained sandstone which contains numerous shale lenses in the immediate vicinity of the ore.

The ore can be classified into two types based on mineralization, prefault and postfault. Identification can be established for the prefault ore by color, calcareous cement, and organic content; for the postfault ore by color, paucity of cement, vertical extent, and multitudinous fracturing.

Three postdepositional faults and numerous associated fractures, acting in conjunction with leaching solutions, caused a beneficial enrichment of the original ore body.

## INTRODUCTION

The Black Jack No. r mine lies in the northwestern corner of McKinley County, New Mexico, about half way between Thoreau and Crown Point (fig. r).

It is served by U.S. Highway 66 and State Highway 56 but is more easily located in association with Smith Lake, from which the head frame can be seen. It is some 37 air miles or 5o highway miles northwest of Grants, the principal supply center.

The mine is owned jointly by the United Nuclear Corporation and Homestake Mining Company and is operated by the Sabre—Pinon Mining Division of United Nuclear, with home offices in Santa Fe, New Mexico.

Original exploration drilling which resulted in the discovery of the ore body was instigated by R. D. Bokum, now president of United Nuclear Corporation, in the fall and winter of 1958 and 1959. The critical hole, drilled in the spring of 1959 by the Clyde L. Jones Drilling Company, cut a 2.5-foot streak of 0.20 percent $U_3O_8$. Offsets on this hole traced the mineralization to the east where it eventually developed into the present ore body.

The shaft was sunk in 102 days in the spring of 1959 under the supervision of William A. Buchecker, now vice-president of mining for the United Nuclear Corporation.

Black Jack No. r is situated under the looming cliffs of the Gallup and Gibson rim in a strike valley which slopes gently to the east. This strike valley comprises a part of the southwestern margin of the San Juan Basin and is formed by upwarping and subsequent erosion of the three lower members of the Mesaverde Group. The valley is bounded on the south by the outcrop of the Morrison Formation.

Locally, the terrain is rather extensively transected by deep arroyos and meandering ditches. The alluvial overburden is a product of the Mesaverde erosion and, as such, has the consistency of gumbo mud when wet and fire clay when dry. The combination of deep arroyos and viscous mud, at times, makes automotive maneuvering somewhat difficult.

The vegetation consists of rather sparsely scattered clumps of grass and numerous hedges of tumbleweed and sagebrush. Here and there on some of the higher ridges and north slopes a few scrawny pinon trees have managed to take root and survive on the approximately 12.5 inches of moisture that falls intermittently throughout the year. The land manages to support a few herds of goats and sheep, tended by the indigenous Navajo Indians and their dogs.

## GEOLOGIC SETTING

The collar of the Black Jack No. r mine has been poured at a surface elevation of 7438 feet and the shaft sunk to a total depth of 825 feet. The shaft penetrates Mancos Shale, Dakota Sandstone, Brushy Basin Shale, and the Westwater Canyon Sandstone.

The Mancos Shale is a black marine shale with a variable thickness of from 95o tor 1a0 feet. However, at the mine location the Mancos has been eroded to a thickness of about 280 feet.

The Dakota Sandstone is of continental and marginal marine derivation believed to be of Late Cretaceous age and is uniformly fine-grained, well-sorted, gray to pure white quartz sandstone. The formation in this area generally averages about r 5o feet in thickness and, except for a coal seam near the bottom, is without significant deviation from a uniform and continuous composition. The coal horizon overlies a basal sandstone lens (10 to 15 feet thick) which appears to act as a sort of cover or mantle to the underlying Brushy Basin Shale and results in masking the undulations of the disconformitv. Consequently, the top of this coal seam may be used as a datum plane with some success.

The Morrison Formation is of Late Jurassic age and consists of three members. These, in descending order, are the Brushy Basin Shale, Westwater Canyon Sandstone, and the Recapture Shale.

The Brushy Basin Member averages about 14o feet in thickness and is composed of a green to grayish shale of continental deposition, here and there split by discontinuous to continuous sandstone lenses somewhat similar in composition to the Westwater sands. Located at the base of the Brushy Basin is the Poison Canyon sandstone which may be more properly included with the underlying Westwater Canyon.

The Westwater Canyon Member in this area averages about 200 feet in thickness and is roughly divided into two equal parts by a continuous shale bed. The shale is reddish brown to tan and varies from 15 to as much as 35 feet in thickness. On its upper profile, it interfingers with the upper Westwater Canyon sand and is scoured by numerous discontinuous stream channels. These channels in places seem to have acted as depositional traps for ore pods.

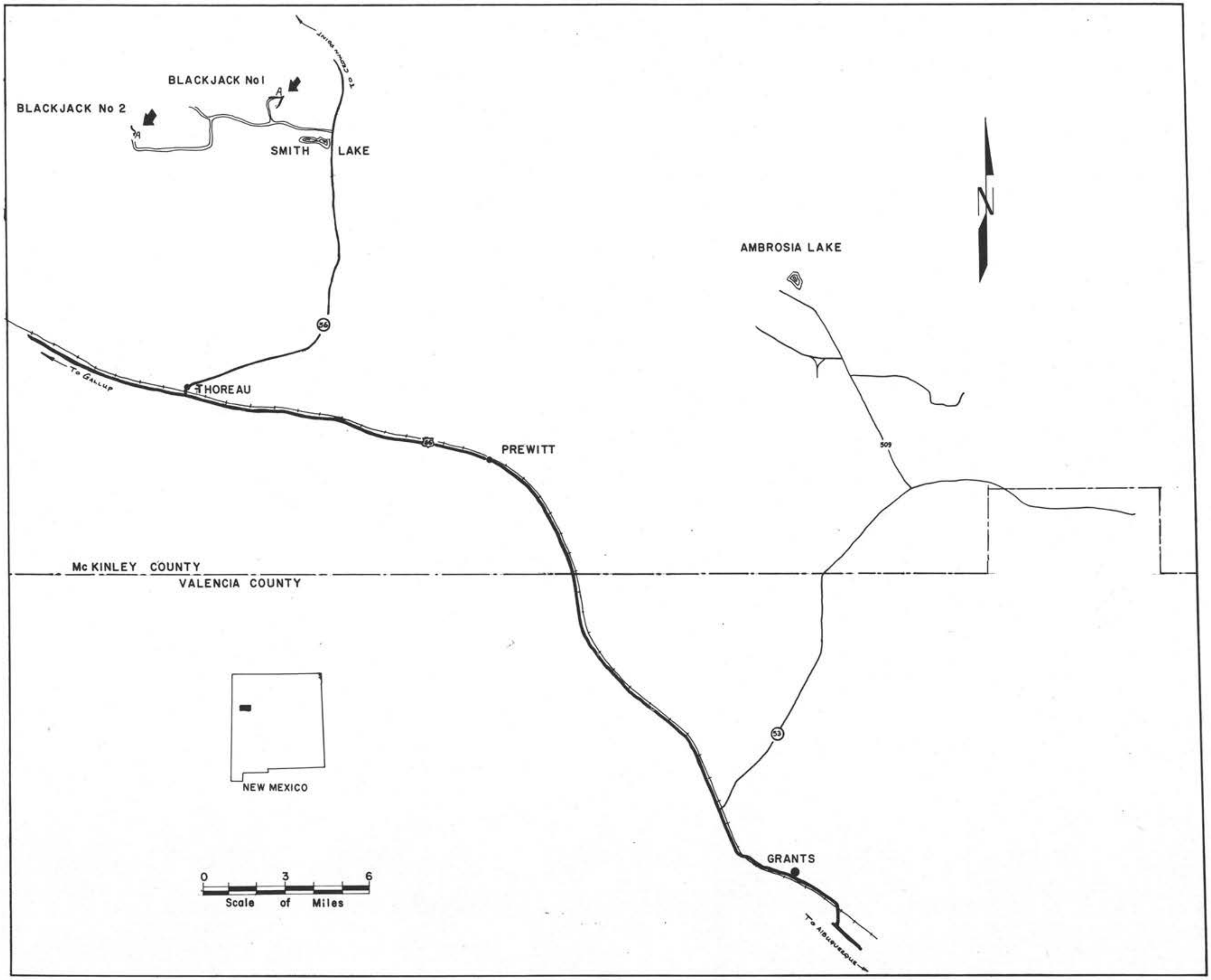


Figure 1

Index map showing location of the Black Jack No. 1 and No. 2 mines

The upper part of the Westwater Canyon which carries the ore is characterized by shale breaks. The lower half has no shale breaks, is a well-sorted sand, is brick-red and contains no known ore. Texturally, the upper sand runs from coarse arkosic to very fine-grained, with rather arbitrary sorting throughout. However, a typical channel festoon will grade downward from fine-grained to coarse arkosic sandstone or thin conglomeratic mudstone at the base.

Festoons and current lineations show a general east-west direction with some local variations in the southwestern portion where they are oriented in a northeasterly direction.

In plan, the ore body shows a color halo that subtly changes from a brick-red to orange or yellow to brown to gray or bleached sandstone. This halo is also maintained in the vertical, and as in most Ambrosia Lake mines, the ore is usually confined to the bleached and gray sandstone.

Originally, the ore was probably in two elongate pods, one trending easterly and the other trending northeasterly so that they formed a roughly V-shaped deposit with the nose pointing to the east. The remnants of this original deposition are represented by the black, asphaltic, limy ores, as seen in the north elongated ore body. The southern wing has been extensively faulted and fractured so that the original deposit has, for the most part, been obscured by the secondary mineralization.

## STRUCTURE

The primary structural control is thought to be the Mariano anticline with which the deposit is closely associated *(see* Hoskins, this memoir, fig. 2). The Mariano anticline plunges about S. 8o E. The deposit lies mostly along the northern flank of the anticline with its eastern extremity about at the shoulder while the northern wing lies along the dome slope-off and the southern wing catches the pitch of the dome flank. This feature has exerted considerable influence on the mining operation, as the lowest stratigraphic horizon to the south is higher in sea level elevation than the stratigraphically highest ore to the north.

Dimensionally, it is a shoestring type of deposit. The main north body has a length of 360o feet, while the average width is only 150 feet. The southern extension generally appears to have had about the same dimensions, but mineral reworking has obscured the original outline. Nonetheless, the length can be traced for 300o feet and the present width averages 200 feet. On the other hand, the thickness of the pods may vary anywhere from a minimum of a few inches to a maximum thickness of 35 feet. In the stacked area mineralization may be I oo feet, the total thickness of the section, although not all may be mineable ore.

The major fault system consists of a number of north-trending strike-slip faults. Three of these faults intersect the ore body and their influence can be seen in the mine openings. (fig. 2).

Fault No. r strikes N. 5 E., where it cuts the ore, and has an easterly dip of 8o to 90 degrees. It is a strike-slip fault with an apparent throw of about five feet. Fractures, slickensides, and fault gouge indicate a rake of about 45 degrees with the west block moving north in relation to the east block. Maximum horizontal movement here has been estimated at about ten feet. The fault is rather tight and shows very little activity by mineralizing solutions. Extensive drilling along the trace has produced some substantial anomalies but nothing of ore grade.

Fault No. 2, located 1050 feet east of No. r, strikes N. 10 E. and has a dip of 85 to 90 degrees to the east. This appears to be a normal fault as it shows about three feet of vertical displacement but no horizontal movement. The trace of No. 2 can be followed continuously for some 400 feet but it seems to have pinched out somewhere between B and R stopes. About six inches of fault gouge and breccia is contained in the fault, and the relatively bleached and friable nature of the breccia strongly indicates that this fault acted as a major channel for the secondary mineralizing activity that is everywhere apparent in the vicinity of this fault and its associated fractures, especially on the upper horizons.

Fault No. 3, is some 320 feet east of Fault No. 2 and has a strike that varies from N. 5 W. to N. 10 E. The dip ranges from 7o degrees east to vertical. This fault can be traced for 2500 feet and intersects every major secondary depositional area in the mine. Here also, the fault is extremely bleached, brecciated, and friable. It generally contains no mineralization, although the breccia attains a width of 18 inches in some areas. Transcurrent movement along this fault is estimated to be 3o to 4o feet with the west block moving north in relation to the east block. Two other minor faults (?) intersect No. 3 at an angle of 55 degrees, one half way to the south ore limit and one at the south limit of the ore.

Numerous shear fractures lie between Faults No. 3 and No. 2. These fractures are invariably oriented N. 45°-55° E. or somewhat parallel to the two minor faults (?) mentioned above. The fractures can be traced for a few inches to as far as 500 feet and vary anywhere from hairline expressions to widths of several inches. Here, too, the fractures show evidence of having acted as solution channels during secondary mineralization. Briefly, areas of numerous fractures show definite secondary enrichment while areas of no, or few fractures, show little or no mineralization at all.

## MINERALIZATION

Indications are strong that at least two periods of mineralization took place. These are prefault or primary and post-fault or secondary.

The prefault ore is in the northern and western parts of the mine and expresses itself in the long, continuous and sinuous black ores of that area. These ores are restricted to two horizons which show minor fracturing, and the sandstone host rock is well cemented with about r o to 15 percent calcite. The ore mineral is believed to be the uranium silicate, coffinite. Also, native selenium and minor amounts of the blue sulfide of molybdenum have been located near the margins of this ore.

Postfault ore is associated intimately with the well-fractured and faulted area in the eastern end of the mine. Here, the ore has been deposited in at least seven more or less distinctive horizons. Depositional control can probably be ascribed to at least two major factors: (1) the presence of numerous continuous shale breaks and, (2) permeability of the rock coincident with the trace of the fractures and faults. Without the presence of both these factors, mineral migration and redeposition could not have occurred to the extent that it has.

The following elements have been identified by spectrographic analysis through the courtesy of Gene Grutt of the U.S. Atomic Energy Commission. The percentages are reported as the oxide of the elements indicated.

SAMPLE 1, CONTAINS URANIUM

| | | | |
|---|---|---|---|
| Na ... 2.75 | V .... 0.10 | Cu ... 0.01 | Ga ... 0.001 |
| Mg ... 0.40 | Cr ... 0.003 | Sc ... 0. | Ba .... 0.12 |
| Al .... 15.0 | Mn ... 0.30 | Sr .... 0.04 | V .... 0.005 |
| K .... 4.0 | Fe .... 4.00 | Zr ... 0.004 | Pl .... 0.004 |
| Ca .... 30.0 | Co ... 0. | Mo ... 0.75 | Yb ... 0. |
| Ti .... 0.10 | Ni ... 0.001 | U .... 0.12 | |

SAMPLE 2, CONTAINS NO URANIUM

| | | | |
|---|---|---|---|
| Na ... 2.25 | V .... 0.20 | Cu ... 0.01 | Sn ... 0.002 |
| Mg ... 0.40 | Cr ... 0.005 | Sc .... 0. | La ... 0.001 |
| Al ... 12.50 | Mn ... 0.02 | Sr .... 0.02 | Ba ... 0.12 |
| K .... 5.00 | Fe .... 4.50 | Zr .... 0.02 | V .... 0. |
| Ca ... 0.50 | Co ... 0. | Mo ... 0. | Pb ... 0.005 |
| Ti .... 0.30 | Ni ... 0.002 | U .... 0. | Yb ... 0. |

The following elements were checked but not found:
Al, Ag, W, Sb, Cd, As, Zn, B, P, Bi, Nb, Ta, Li, Tl, Au, Te, Be, Pt, Ge, Th, In.

The above are typical, though random, samples. Secondary minerals have been tentatively identified as carnotite and tyuyamunite.

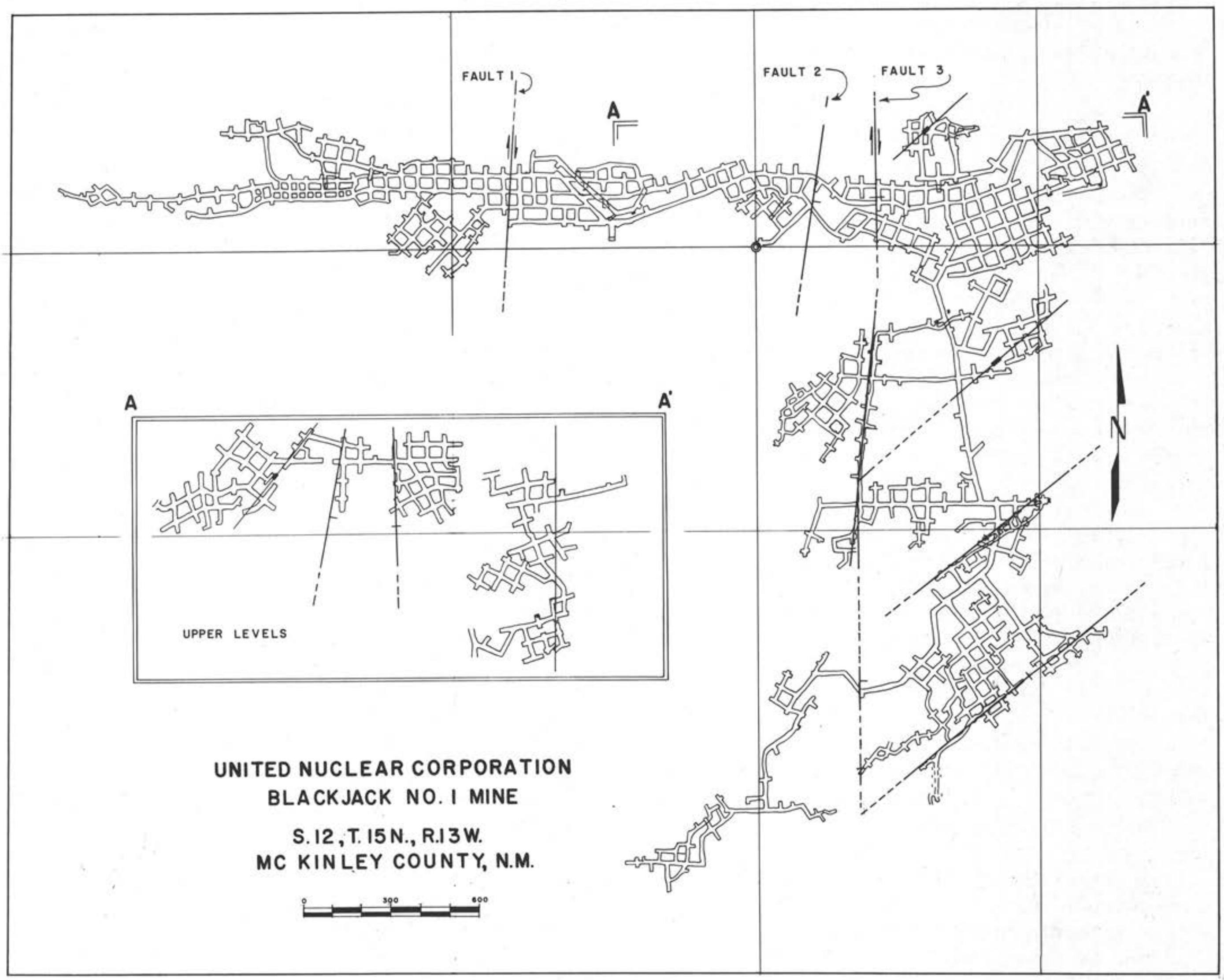


Figure 2
PLAN MAP OF THE BLACK JACK NO. 1 MINE

# Geology of the Black Jack No. 2 Mine, Smith Lake Area

WILLIAM G. HOSKINS

The Black Jack No. 2 mine is about eight miles west of Smith Lake in sec. 18, T. 15 N., R. 13 W., McKinley County, New Mexico *(see* MacRae, this memoir, fig. i ). The mine was brought into production early in 196o and has been in constant production since then.

The ore is mined by driving 14 x 8-foot drifts and crosscutting on 50-foot centers where ore permits. The ore is hauled on diesel equipment to the shaft.

The ore occurs below the water table in a sandstone interbedded with mudstone lenses. The over-all outline of the ore body gives an appearance of being a stream channel.

## STRATIGRAPHY

The mine is in the Brushy Basin Member of the Morrison Formation. This member is about 150 feet thick and consists of a greenish gray mudstone. In the mine vicinity, it is divided into two layers by a standstone lens known as the *Poison Canyon tongue,* which is the host rock of the ore (fig. 1 A-A'). At the mine, the Poison Canyon sandstone is about 6o feet thick in the northwestern end and thins to 18 feet in the south end. This sandstone thickens and thins locally and pinches out two to three miles east of the mine.

In the southern end of the mine, the sandstone is free of interbedded seams of mudstone, but the northwestern portion of the mine has two to three layers of mudstone. The layers range in thickness from 1 to 8 feet. (fig. 1 B-B').

The sandstone in the areas mined is generally tan to dark brown, with the exception of the northeastern edge of the mine where the sandstone turns to a brick-red color. The change in color is sharp and forms the ore boundary by this line.

Grain size of the sandstone ranges from medium to very coarse. The very coarse material is usually found lying directly on a mudstone. The sandstone is highly cross-bedded and somewhat graded. This sandstone is largely composed of angular to subangular grains of quartz and pink feldspar.

## STRUCTURE

The Black Jack No. 2 mine lies mostly along the axis of a syncline formed between the regional dip and the Mariana anticline (fig. 2). The regional dip of the beds ranges from 3 to 5 degrees to the northeast. The southwestern flank of the anticline also dips 3 to 5 degrees. The ore body plunges with the syncline to the northwest.

The rocks in the mine have been cut by a set of steeply dipping fractures. The fractures strike N. 55° W. and dip slightly to the northeast. The fractured zones are usually one half to one inch wide and are locally filled with a clayey gouge material. Occasionally, ore has been leached two to three inches from the fractures, leaving a reddish brown color to the sandstone. The ore trends do not seem to have been influenced by the fractures.

## DESCRIPTION OF ORE BODY

The over-all ore body consists of interconnecting pods, a fish hook trend, and isolated pods (fig. 3). The ore bodies are generally lenticular in shape and pinch out rapidly on the northeastern side of the mine. Some of these lenticular bodies interconnect and overlap along the longitude of the mine. Usually these interconnecting ore tongues are of low grade. Occasionally, a streak of high-grade ore one to two feet thick and five to ten feet wide connects the ore bodies.

There are three ore horizons in the mine, but most of the ore occurs in the lower part of the ore-bearing sandstone, usually lying directly on the lowest mudstone (fig. 1 B-B', D-D'; fig. 4). Locally, the lower edge of the ore may be two to five feet above the mudstone, but it usually dips back to the mudstone and conforms to it. Locally, ore pods occur under mudstone layers that are suspended in the sandstone. The highest grade of ore is usually in very coarse-grained sandstone having a black oily color, which is called "greasy ore" by the miners.

## ORE CONTROLS

Varying permeability of the sedimentary structures probably has the most influence on the detailed shapes of the ore bodies. The ore is of higher grade and thicker in the vicinity of highly cross-bedded sandstone, usually becoming less mineralized as the sand reduces in coarseness. The lower mudstone layer has acted as a barrier for the over-all ore body. In places where the ore seems to be floating in the sandstone, usually a thin seam of small mudstone pellets underlies the ore.

The brick-red sandstone is the ore boundary and forms a sharp line along the northeastern side of the mine. In general, the sandstone seems to be cross-bedded and of the same quality as the ore-bearing sandstone, but of brick-red color. No mineralization so far has occurred in this red sandstone.

The ore body is elongate in the general direction of the fracture set; however, the main ore bodies cross the fractures. The edge of the ore forms a sharp line and does not round horizontally into the fractures where crossed.

In general, the ore indicates that it is following an ancient stream pattern. The ore ends abruptly across the trend, but long continuous stringers of ore connect and overlap the main ore bodies in a longitudinal section. The surface drilling program supports this trend, as more small mineralized pods have been located one to two thousand feet northwest and three to four thousand feet southwest of the main ore body.

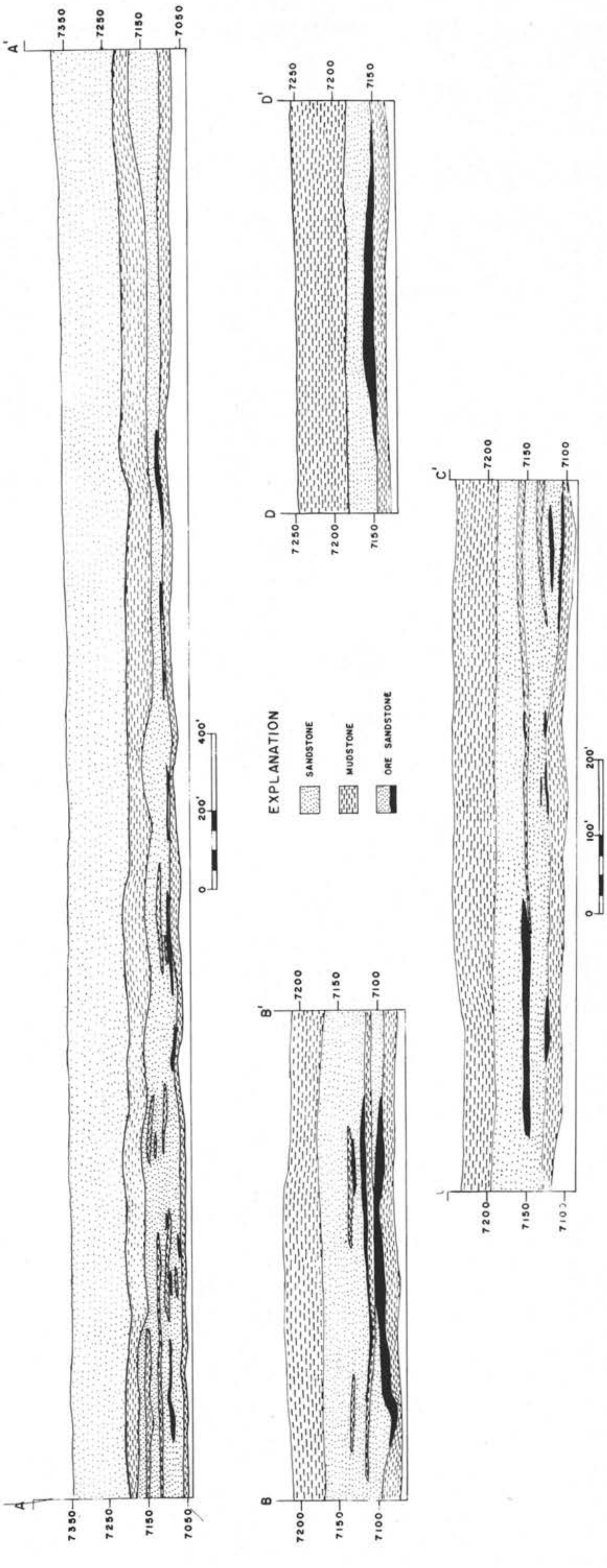


Figure 1

GEOLOGIC SECTIONS OF BLACK JACK NO. 2 MINE

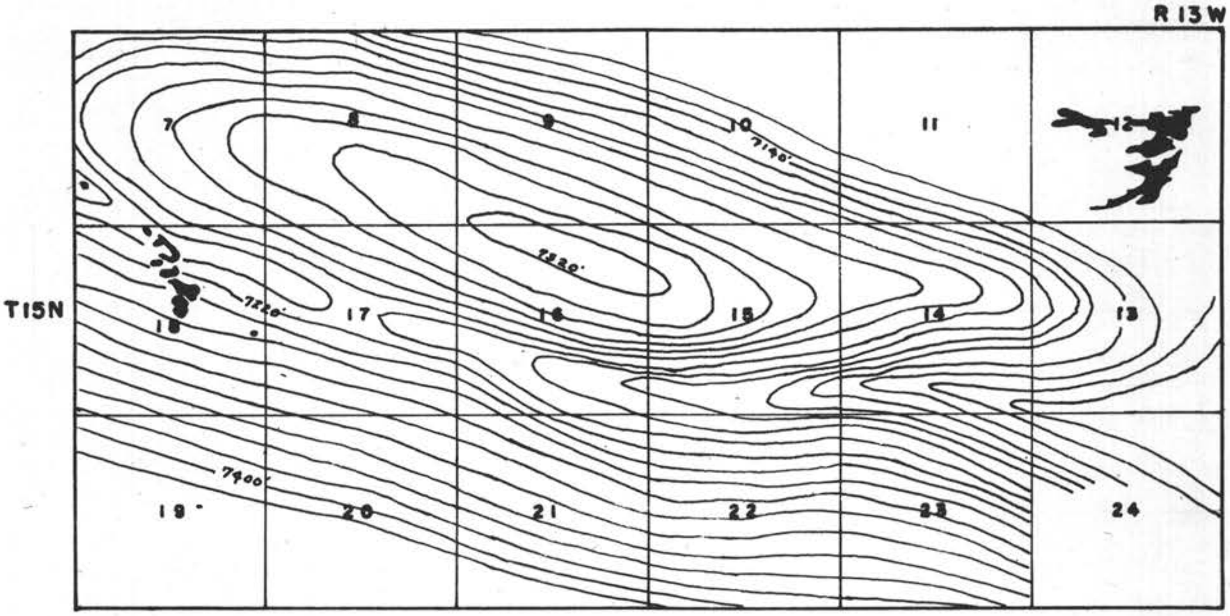


Figure 2

Structure contour map on base of Dakota Sandstone and showing ore bodies (black)

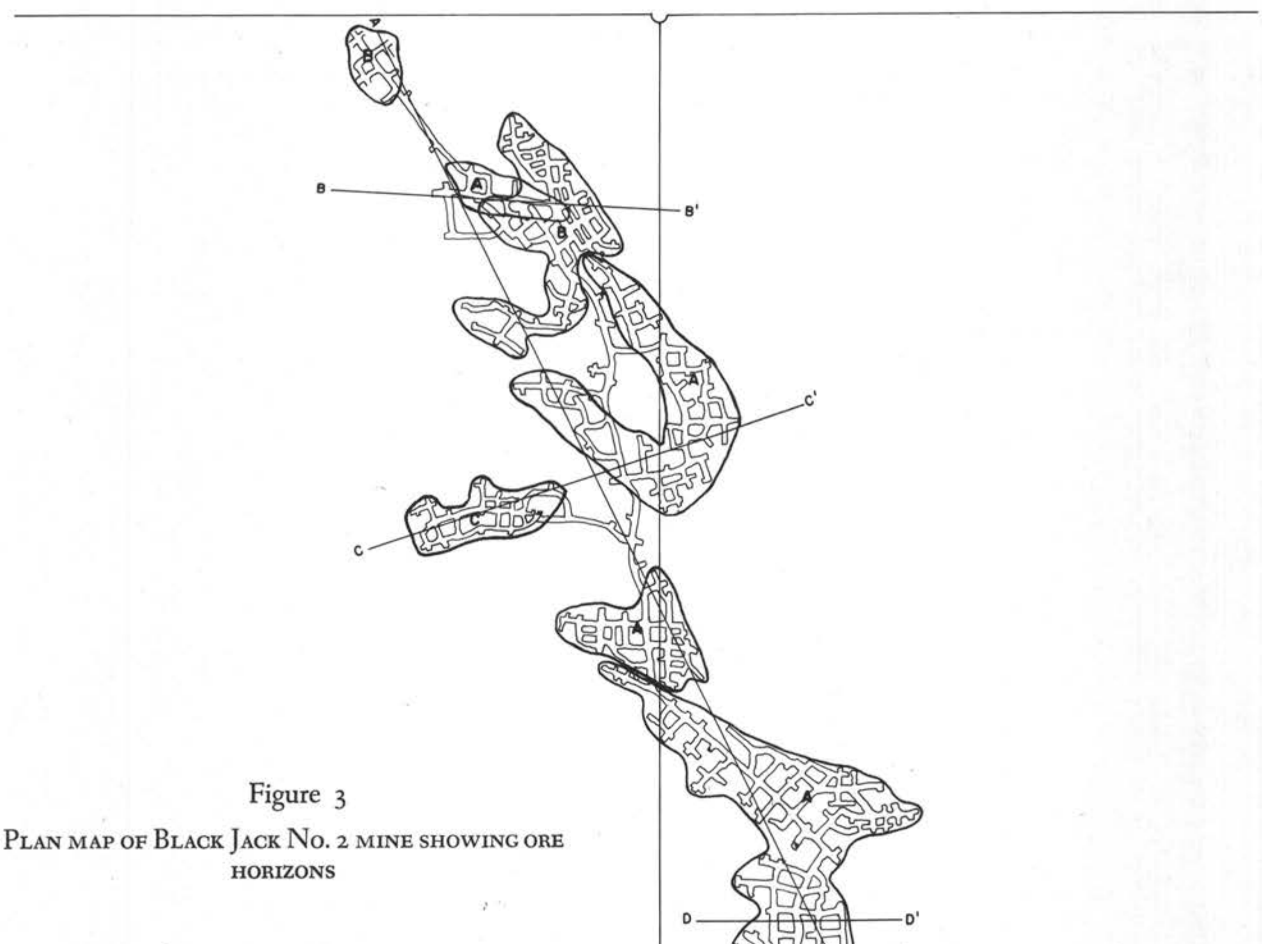


Figure 3

Plan map of Black Jack No. 2 mine showing ore horizons

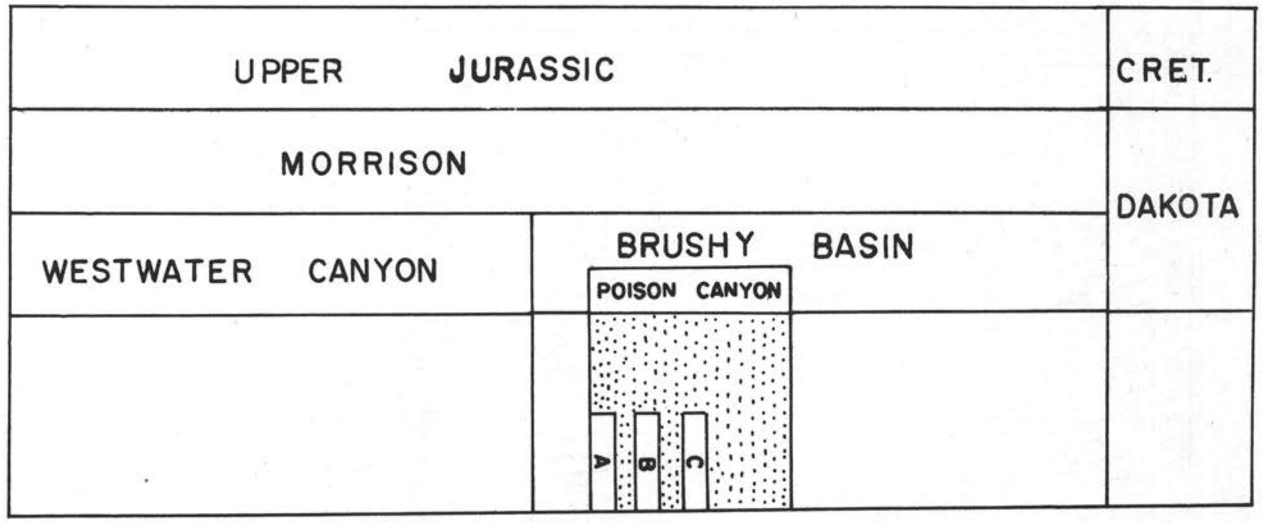


Figure 4

DIAGRAMMATIC SECTION OF ORE-BEARING SANDSTONE

## MINERALOGY

The ore in the mine is all below the water table and consists of unoxidized uranium and vanadium minerals. Oxidized minerals do occur as streaks on the ribs after the areas have been mined out.

To date, no samples have been examined to determine the mineral suites. The ore minerals are probably of the low-valence orders coffinite and vanadium silicates. No woody material or "trash" has been observed, but the black, greasy ore is probably due to carbonaceous material.

## CONCLUSIONS

The mudstone layers have acted as a barrier for the ore bodies and may have played some part in precipitating the ore. The sedimentary structures and permeability of the sandstone are probably the major controlling features of the ore. Fractures show little or no controlling relationship to the ore. The brick-red sandstone is not mineralized and acts as a tool for drilling operations. Carbonaceous material is probably responsible for some high-grade pods of ore.

# *Relation of Ore Deposits to the Stratigraphy of Host Rocks in the Ambrosia Lake Area*

E. S. SANTOS

## ABSTRACT

Ninety percent of the uranium ore in the Ambrosia Lake area occurs in the Westwater Canyon Member of the Morrison Formation of Late Jurassic age.

The ore deposits of the area are clustered into the Ambrosia Lake trend and the Poison Canyon trend. Ambrosia Lake-trend deposits all occur where the Westwater Canyon is more than 200 feet thick. The position of the Poison Canyon trend is not related to the thickness of the host rocks. The Ambrosia Lake trend is divided into three zones according to the stratigraphic position of ore bodies. In zone 1, ore occurs only in the upper one third of the member; in zone z, only in the upper two thirds; and in zone 3, from top to bottom of the member.

The location of the district as a whole does not appear to be controlled by changes in thickness or lithology of the Westwater Canyon Member.

Some of the ore was deposited before faulting and was controlled locally by small-scale sedimentary features; part of the ore was redistributed after faulting and was controlled by a combination of sedimentary features and tectonic structures.

## INTRODUCTION

In the Ambrosia Lake area, uranium ore deposits occur in the Westwater Canyon Member of the Morrison Formation of Late Jurassic age, in the Todilto Limestone of Late Jurassic age, and in the Dakota Sandstone of Early and Late Cretaceous age. More than 90 percent of the ore in the district occurs in the Westwater Canyon Member.

Because of their minor importance, relatively little study has been devoted to the Todilto and Dakota deposits. This report deals exclusively with the more important better known deposits of the Westwater Canyon Member, describes the lithology of the Westwater Canyon Member in the Ambrosia Lake area, and relates the position of ore bodies to the stratigraphy of the host rock and to various sedimentary structures.

## MORRISON FORMATION

The Morrison Formation in northwestern New Mexico consists of three members, the Recapture, the Westwater Canyon, and the Brushy Basin. The Morrison Formation is overlain unconformably by the Dakota Sandstone and underlain by the Bluff Sandstone.

Intertonguing of mudstone and sandstone facies in the upper half of the Morrison Formation has caused disagreement in placing the Brushy Basin—Westwater Canyon contact. Special significance was attached to the zone in which sandstone interfingers with mudstone because early exploration suggested that ore bodies were confined to this zone. Because of the apparent economic importance of this zone, attempts were made to distinguish it from what was believed to be barren sandstone below it by including it in the Brushy Basin Member. Subsequent exploration found ore bodies distributed throughout all the sandstone facies in the middle part of the Morrison.

The discovery of ore bodies in the lower part of the sandstone facies obviates the differentiation on an economic basis and indicates rather that the sandstone should be grouped into a single unit. This revision would be more natural in that it would group rocks of identical lithic character and serve as a unit of economic interest as well. In this paper, therefore, all the arkosic sandstone facies above the Recapture Member and below the thick green mudstone at the top of the Morrison Formation is considered to be the Westwater Canyon Member. According to this definition, all mineable ore in the Morrison Formation in the Ambrosia Lake area is contained in the Westwater Canyon Member.

Smith (1954) differentiated the sandstone facies of the Morrison Formation in the Thoreau quadrangle west of Ambrosia Lake into a lower barren facies, which he named the Prewitt Sandstone Member, and an upper mineralized facies, which he included in the Brushy Basin Member. He noted differences in lithology and sedimentary structures between the two facies in the Thoreau quadrangle, but these differences are absent or very indistinct in the Ambrosia Lake area.

In the Ambrosia Lake area the name *Poison Canyon Sandstone* of Zitting et al. (1957) was applied to a particularly persistent sandstone unit at the top of the sandstone facies. This unit is separated from the sandstone below it by up to 4o feet of mudstone similar to the mudstone of the Brushy Basin Member. The unit is traceable along the outcrop for about seven miles. A number of ore deposits occur exclusively within this unit and compose a discrete belt within the Ambrosia Lake area. Northward from the outcrop, this unit merges with the main body of the Westwater Canyon Member, and, throughout the greater part of the district, it cannot be distinguished as a separate unit. This unit is also considered as part of the Westwater Canyon Member in this report.

The Brushy Basin Member in the Ambrosia Lake area is mainly a grayish green mudstone but includes minor amounts of sandstone and sandy mudstone. Erosion at the top and interfingering with the Westwater Canyon at the base produce a range in thickness of from 6z to 128 feet. The Brushy Basin forms a steep slope.

The Westwater Canyon Member is mainly an arkosic sandstone but includes minor amounts of layered mudstone. Intertonguing with the overlying Brushy Basin and the underlying Recapture produces a range in thickness of from

30 to 270 feet in the Ambrosia Lake area. Because it is the principal host for uranium deposits in the area, the Westwater Canyon is described in more detail below.

The Recapture Member consists of alternating variegated greenish gray, purplish, and grayish red mudstone, siltstone, and sandy siltstone, and it includes minor amounts of buff and light gray to white sandstone. The Recapture ranges in thickness from 137 to 232 feet and forms steep slopes and badlands.

## WESTWATER CANYON MEMBER

The Westwater Canyon Member extends throughout part of northeastern Arizona and northwestern New Mexico. The member attains its maximum thickness of 33o feet 3o miles north of Gallup (Craig et al., 1955). To the north, northeast, and east, it tongues and grades into the lower part of the Brushy Basin Member. To the south, it thins to extinction along an east-west line passing through a point 3o miles south of Gallup. The facies distribution of the Westwater Canyon indicates that its source was in west-central New Mexico, from an area of pre-existing igneous, metamorphic, and sedimentary rocks. This member formed as a broad, fan-shaped, alluvial plain traversed by alluviating braided streams (Craig et al.).

In the Ambrosia Lake area, the Westwater Canyon Member ranges from 3o to 270 feet in thickness. It forms massive cliffs and ledgy slopes. The color of the sandstone varies. At the outcrop, the colors are pale yellowish gray, reddish brown, and yellowish orange. Below the surface, the colors are light gray, pale yellowish orange, dark yellowish orange, dusky red, and moderate reddish brown. Mudstone beds, from less than one inch to more than 30 feet thick, are interbedded with the sandstone. These beds are thicker, more numerous, and more continuous in the upper one third of the member. The beds of mudstone, generally grayish green but in places mottled red, are identical with the mudstone of the overlying Brushy Basin Member.

Sand grains are principally quartz, feldspar, and chert in variable proportions. Quartz ranges from 56 to 90 percent, feldspar from 3 to 33 percent, and chert from 1 to 28 percent. Heavy minerals, other than pyrite, constitute less than half of one percent of the total grains (Cadigan, oral communication). Cementing materials are calcite, iron oxide, and clay. Kaolinite in the form of small white nested clusters is a common conspicuous component. Mudstone pebbles, cobbles, and boul ers are scattere throughout the sandstone.

The sandstone is everywhere cross-bedded. Cross-stratification is mainly of the high-angle, medium-scale, trough type and less commonly of the low-angle, large-scale, simple type (McKee and Weir, 1953). Grain size ranges from very fine to very coarse. The degree of sorting is extremely variable from bed to bed. Generally, the fine-grained sandstone is well sorted and the coarse-grained, poorly sorted. The degree of induration is also extremely variable, depending on the amount and type of cementing material present. Very hard calcitic sandstone forms layers, lenses, concretions, and irregular-shaped masses.

Many small-scale intraformational disconformities occur throughout the Westwater Canyon Member. The traceable extent of the disconformities is generally only a few tens of feet but, rarely, is as much as several hundred feet. Disconformities terminate by dying out into bedding planes or by being cut out by another disconformity. Disconformities are frequently marked by a thin layer of mudstone conglomerate tightly cemented by calcite.

Measurement of current lineations in many mines indicates that the orientation of the streams that deposited the sandstone was northwest-southeast in the lower two thirds of the member and northeast-southwest in the upper one third. The direction of stream flow, unfortunately, could not be ascertained with any degree of confidence from the current lineation measurements.

## SEDIMENTARY ORE CONTROLS

Two types of ore are recognized in the Ambrosia Lake area: prefault trend ore and postfault redistributed ore* (Granger et al., 1961). Individual ore bodies may consist entirely of one type or the other, but most commonly they are combinations of the two types. Deposition of trend-type ore was controlled entirely by sedimentary structures, whereas deposition of redistributed ore was controlled by a combination of sedimentary and tectonic stuctures.

Trend-type ore bodies are virtually flat-lying manto masses elongate in an east-southeasterly direction. Small-scale details of ore distribution within these bodies are closely associated with sedimentary phenomena such as disconformities, bedding planes, mudstone-conglomerate beds, and calcite cementation.

Within trend-type deposits, many ore layers occur parallel to disconformities. The ore layer may be entirely above, entirely below, or it may enclose the disconformity. The ore layer may be a thin discrete band or may grade out gradually in the direction perpendicular to the disconformity. Where a disconformity terminates by dying out into a bedding plane, the ore layer may terminate abruptly, grade out gradually Within a short distance, or swing upward or downward to follow another sedimentary discontinuity. Some ore layers are in direct contact with the disconformity; others are separated from it by a few inches of barren sandstone, which may or may not be tightly cemented by calcite. Irregularities on the surface of the disconformity are usually reflected on the proximal boundary of the adjacent ore layer.

Bedding surfaces form the boundaries of ore layers in many places in trend-type ore bodies. Ore is frequently seen ending abruptly along a bedding plane. Elsewhere, the ore may cut across this bounding surface only to be contained by an adjacent bedding plane. Usually, it is the bottom of an ore layer that is bounded this way. The ore layer or zone above the boundary may completely engulf many other equally prominent bedding planes and grade out gradually upward. Where ore layers grade out laterall , thin feathery extensions of ore into barren rock follow bedding panes. Within the ore zone, darker strea s of presumably high-grade ore are concentrated along bedding planes.

Mudstone in certain forms is related to ore deposition in the prefault ore bodies of the district. Ore is commonly associated with thin, discontinuous mudstone lenses, isolated mud-stone cobbles and boulders, and mudstone-conglomerate beds.

* Others elsewhere in this memoir use the term *stacked ore* for similar deposits.

Halos of ore commonly surround thin mudstone lenses and isolated cobbles and boulders of mudstone. The relationship is especially striking in access drifts driven through barren san 'stone. In these places, which may be 5o to 1 oo feet from an ore zone, the only mineralized rock to be seen is in thin dark halos surrounding mudstone fragments.

Mudstone conglomerates are pebbles and cobbles of mudstone in a coarse to conglomeratic sandstone matrix. Where the conglomerate forms a bed, generally just above a disconformity, uranium ore is associated with the conglomerate in much the same manner as it is with disconformities alone. In some places, a mineralized conglomerate bed constitutes the entire ore layer. In many places, irregular, poorly defined zones of mudstone-pebble conglomerate are ore-bearing. That the conglomerate provides a more favorable environment for deposition of uranium is indicated by the way in which the ore grades out as the conglomerate facies grades into sandstone facies.

The relationship of ore layers to thick mudstone beds is not clear. Electric logs of holes drilled in ore bodies show many ore layers in contact with, just above, or just below, thick mud-stone beds. In the mine workings, however, this is seldom seen. In some places, there is a barren zone separating ore layers from the thick mudstone beds, but, in most instances, the practice of driving drifts to avoid mudstone backs or sills frustrates efforts to verify the relationship indicated by the electric logs. Tightly cemented calcitic sandstone layers appear to form the boundaries of ore in a Few places in the district. Trough out a large part of the Marquez mine, the ore zone is underlain by one to two feet of very hard, barren, calcitic sandstone. The relationship here suggests that the calcitic sandstone layer formed an impermeable barrier against which the ore was deposited.

In most places, however, the relationship of ore to calcitic sandstone is not so clear cut as for other sedimentary controls. In places, an ore layer may be tightly cemented, whereas the adjacent barren sandstone is very friable. In other places, part of an ore zone may be impregnated and part of it may be relatively free of cement. Very hard, barren, calcitic sandstone concretions are, in places, completely surrounded by ore. Apparently, there has been much solution and redeposition of calcite since the deposits were formed.

In all the thinsections examined, the calcite appears to be later than the ore. This might suggest that all the calcite in and near ore bodies is later than the ore and could not have controlled the deposition of the uranium, as it appears to do in the Marquez mine. It is possible, however, that some of the calcite in barren sandstone predates ore deposition and could have controlled it.

In redistributed ore bodies, the typical west-northwest elongation characteristic of prefault ore bodies is absent or modified to some extent. Redistribution of uranium along faults or fractures results in elongation of the ore body parallel to these structures or in irregular-shaped masses with no particular trend. Segregation into thin, tabular discrete layers is not so pronounced as in trend-type ore bodies. Most typically, redistributed ore bodies consist of poorly defined layers of ore of no great lateral extent, piled one on top of another and separated from each other by low-grade ore deposits or barren sandstone. Association with sedimentary discontinuities is not so pronounced as in trend-type ore bodies.

## STRATIGRAPHIC POSITION OF ORE BODIES

Ore bodies in the district are clustered into two belts about four miles apart (fig. 1). The area between the belts is not completely barren but contains only small, scattered deposits that appear to consist entirely of redistributed or oxidized ore. In the southern belt, all the deposits occur in the Poison Canyon (Zitting et al., 1957), and the belt has been called the *Poison Canyon trend.* In the northern belt, referred to here as the *Ambrosia Lake trend*, ore deposits occur at all stratigraphic levels in the Westwater Canyon Member (fig. 2).

There is a crude systematic change in the vertical position of ore bodies across the Ambrosia Lake trend. Along the southern margin of the belt, ore deposits occur from the top to the bottom of the Westwater Canyon Member. Through the center of the belt, ore deposits occur from near the middle to the top of the Westwater Canyon, and along the northern margin of the belt, they occur at the top only. The delineation of zones according to the vertical distribution of ore bodies is shown in Fig .ire 1.

Redistribution had undoubtedly altered the original pattern of distribution of ore bodies in the Ambrosia Lake area and accounts for the irregularities and anomalies in the pattern. When enough data have been collected to distinguish prefault from redistributed ore in all the deposits, a more consistent pattern may emerge.

Deposits in the Ambrosia Lake trend occupy an area where the Westwater Canyon member is zoo feet or more in thickness (fig. i ). The position of ore bodies in the Poison Canyon trend, however, does not appear to be related to the thickness of the entire member nor to the thickness of the Poison Canyon. Across the Poison Canyon trend, the Westwater Canyon Member ranges in thickness from 100 to 175 feet. Ore bodies in this belt occur where the thickness of the Poison Canyon Sandstone is as much as 90 feet or as little as 3o feet.

The apparent relationship of ore bodies to thickness in the Ambrosia Lake trend and the complete lack of such relationship in the Poison Canyon trend suggest that thickness of the host rock, in itself, is not a critical controlling factor in ore deposition and cannot be used as an exploration guide.

Electric logs of holes beyond the lateral edges of the district indicate neither an abrupt change in facies nor a consistent change in thickness of the Westwater Canyon Member.

Figure 3 is a series of eight irregularly spaced holes, 400 to 2400 feet apart, extending from the edge of an ore body in sec. 27, T. 14 N., R. 9 W., one and five tenths miles northward into barren ground. Figure 4 is a series of 12 irregularly spaced holes, 600 to 800 feet apart, extending from the edges of an ore body in sec. 33, T. 14 N., R. 9 W., one and five tenths miles southward into barren ground. The Dakota-Mancos -contact is used as a common datum and the part omitted from each section is of uniform thickness.

No drastic nor consistent changes can be seen occurring in the character of the host rock that might account for the limits of mineralization. None of the data collected to date reveals any obvious sedimentary controls that would limit the district, as a whole, to its present bounds.

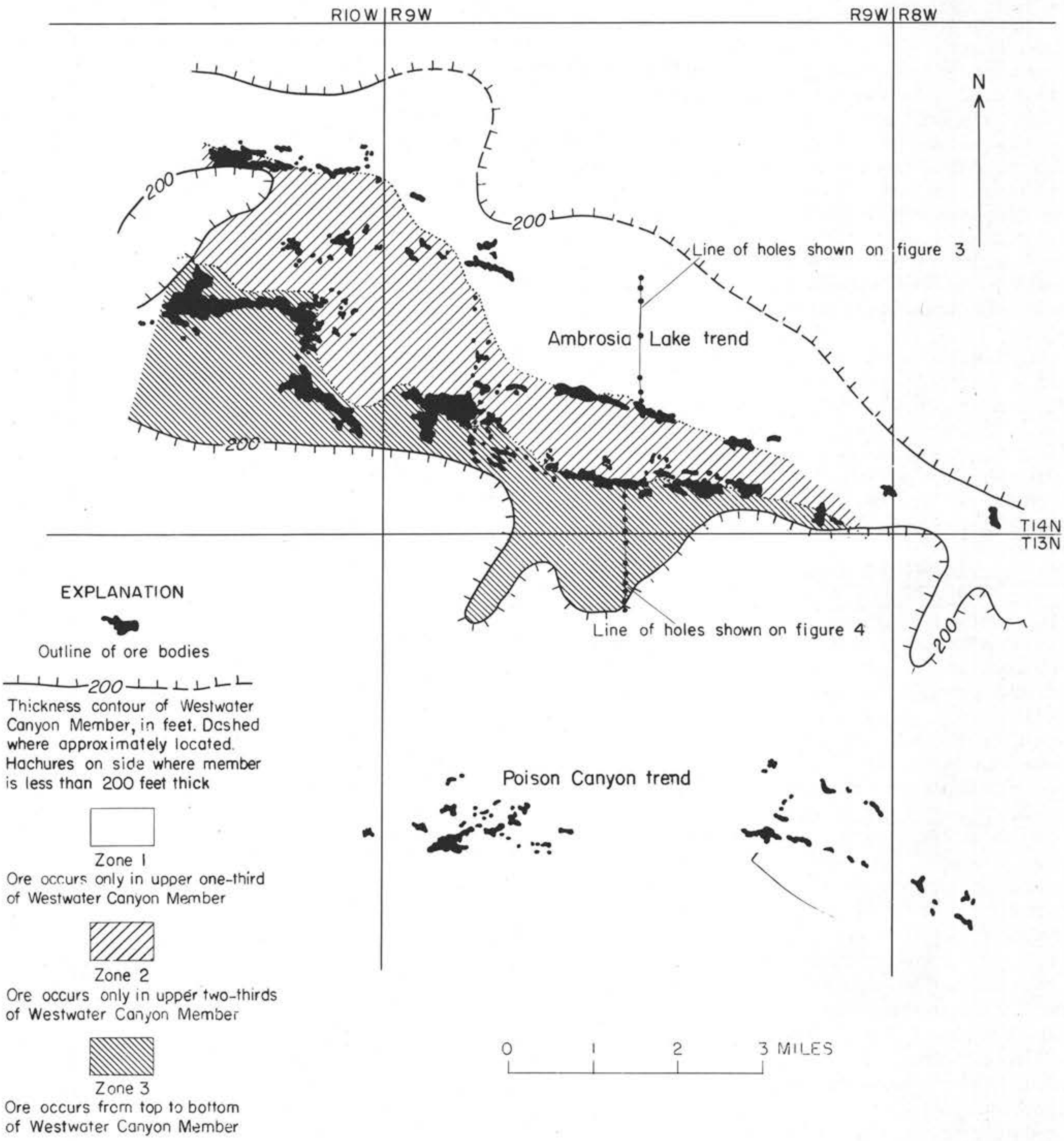


Figure 1

MAP OF ORE DEPOSITS IN THE MORRISON FORMATION, AMBROSIA LAKE AREA

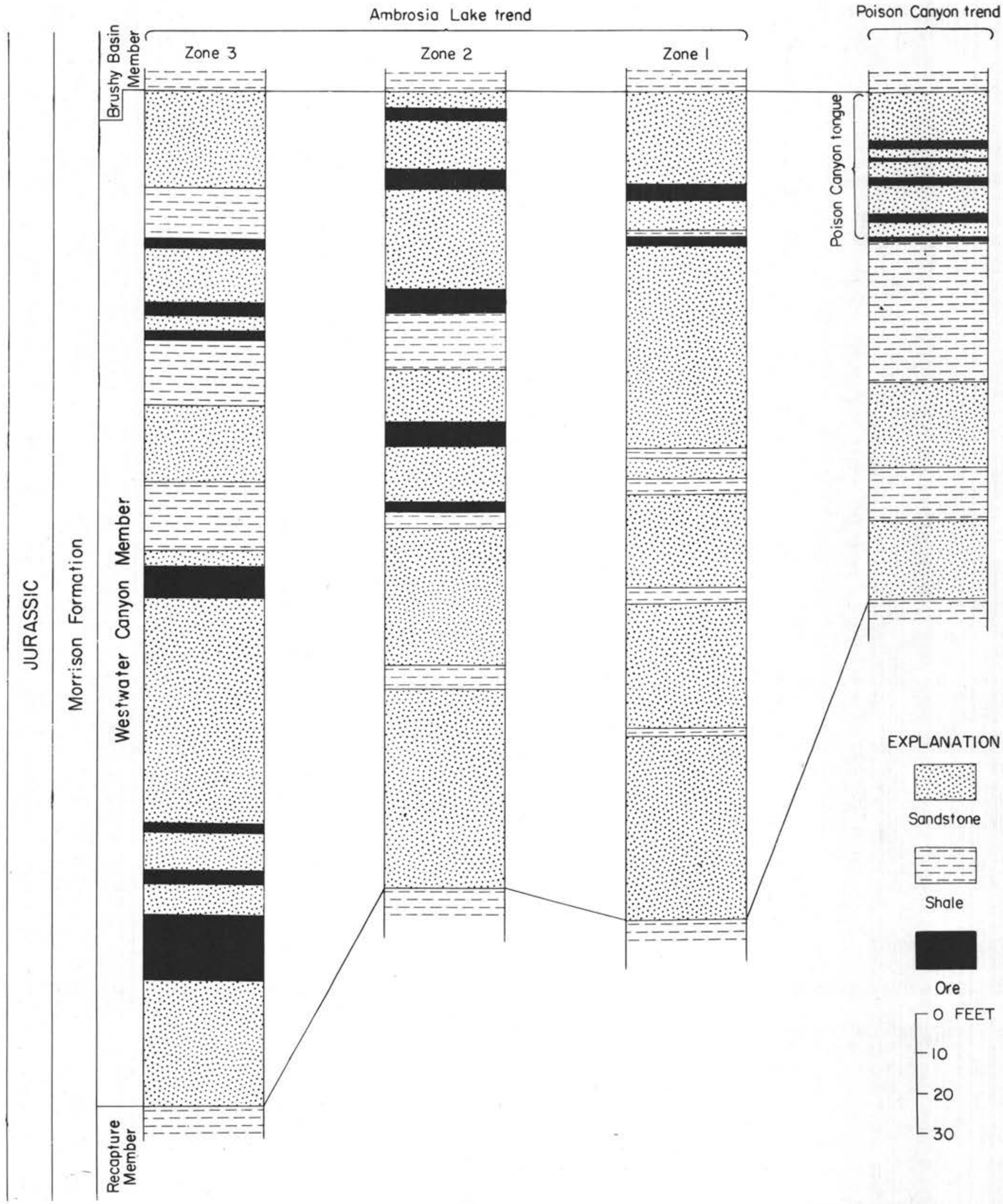


Figure 2

Representative holes showing distribution of ore in the two ore belts

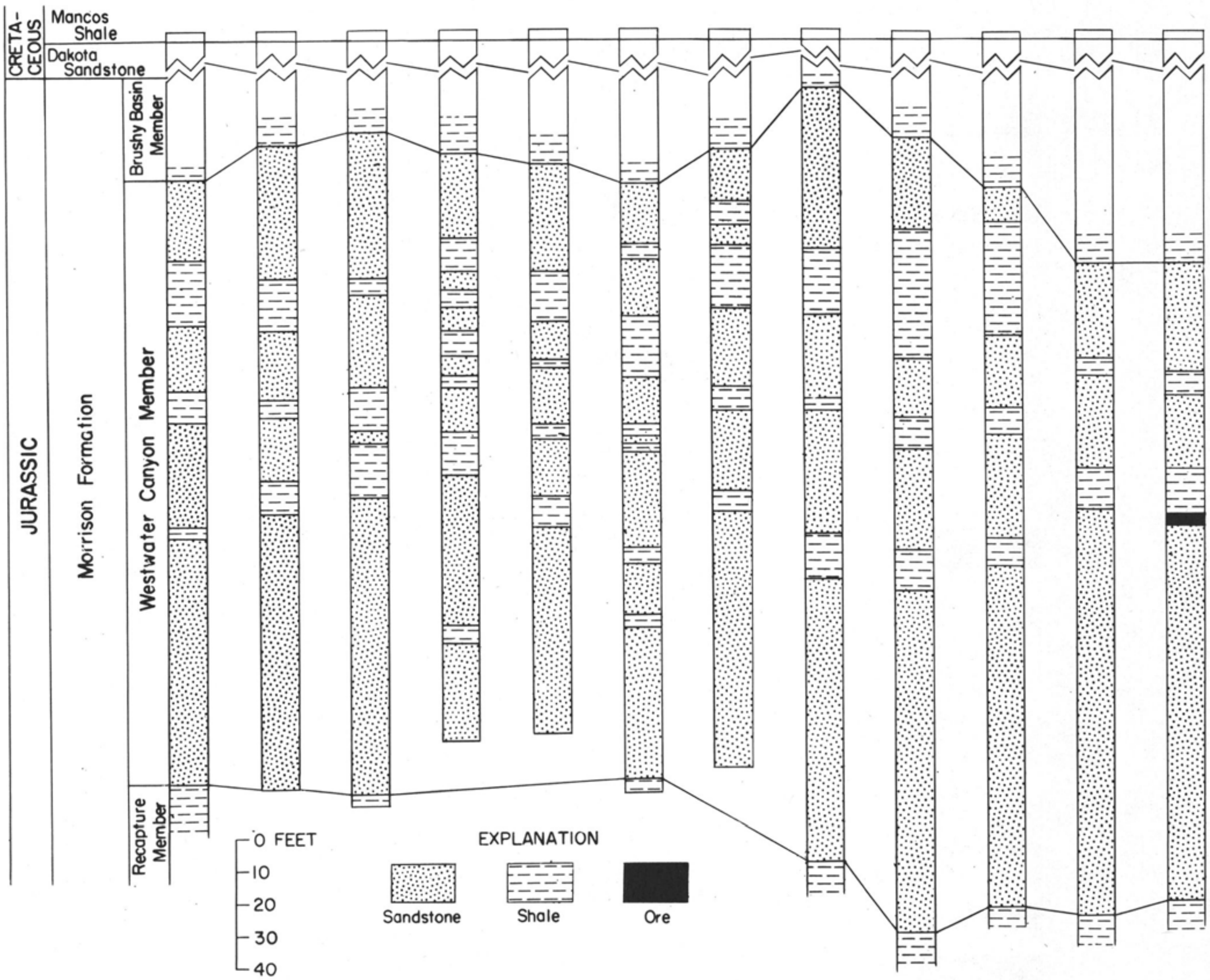


Figure 3

LINE OF HOLES EXTENDING FROM ORE BODY IN SEC. 27, T. 14 N., R. 9 W., ONE AND FIVE TENTHS MILES NORTHWARD INTO BARREN GROUND

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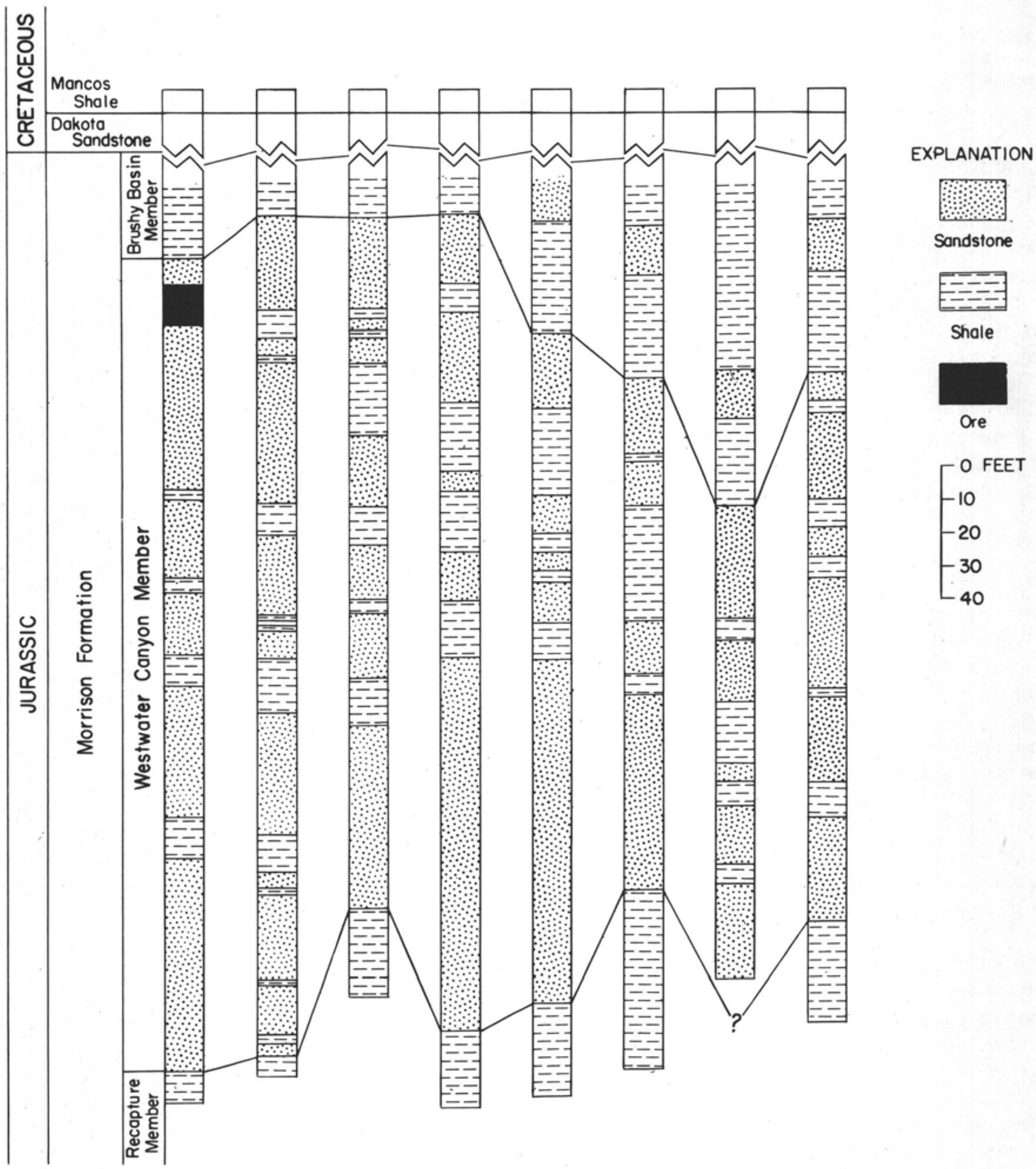


Figure 4

LINE OF HOLES EXTENDING FROM ORE BODY IN SEC. 33, T. 14 N., R. 9W., ONE AND FIVE TENTHS MILES SOUTHWARD INTO BARREN GROUND

# *Geology of the Dysart No. 1 Mine, Ambrosia Lake Area*

R. J. CONK

## INTRODUCTION

The Dysart No. r mine site is in the northwestern part of the Ambrosia Lake area in the SW1/4 sec. II, T. 14 N., R. ro W. [N.M.P.M.]

The mine was one of the first sandstone-type deposits in the Ambrosia Lake area to be opened up and is now mined out. Final production was completed in April, 1961. During the life of the property nearly 900,000 tons of ore were produced at an average grade of .21 percent $U_3 0_8$. Maximum production was approximately 1500 tons per day on a two-shift basis. All workings were completely dry.

The mine was developed by 7 x I 5-foot drifts on 7o-foot centers leaving 55-foot pillars and on 35-foot centers leaving 20-foot pillars. The particular spacing depended upon ground conditions. After complete development the pillars were quartered, extracted, and the unsupported ground allowed to cave behind the line of retreat.

## GEOLOGY

The Dysart No. I mine shaft collars in the Mancos Shale and bottoms in the lower part of the Westwater Canyon Member. The Westwater Canyon Sandstone, which is 120 to 14o feet thick, was the host rock for the uranium ores at the Dysart No. r mine.

The Dysart No. I mine lies on the northern flank of the Ambrosia Lake anticline. The mine is a segment of the trend of ore that starts in the eastern part of the SETA of section 10, and extends across the southern half of section II and into the southwestern part of the adjacent section 12.

The uranium ores were chiefly black with only minor occurrences of secondary uranium ores. There were minor occurrences of molybdenum minerals which were noted in most instances on the fringes of the ore. The color was bluish black and at first sight was confused with the black uranium ore but could be distinguished by its slight bluish cast combined with a low gamma-ray count. A few occurrences of native selenium were found mostly in the southeastern area of the mine.

The ore bodies were generally elongated in an east-west direction with one notable exception, a small north-south ore body in the east-central part of the mine (fig. I ). This ore body was stratigraphically high in the Westwater and was very narrow in relation to its length. The ore body followed north-south fractures and these had yellow uranium mineralization. Some cut-and-fill sedimentary structures also coincided with a north-south trend.

The area to the northwest of the shaft was the most complicated as far as multiple zones of ore were concerned. This area presented not only problems in stoping but earlier problems in interpretation of the ore zones from surface drilling.

The earliest drilling indicated that ore occurred at many different elevations and extreme difficulty was encountered in correlating ore zones from one hole to the next even when holes were drilled as close as l00 feet. As development extended from the shaft, it became evident that the uranium deposit had considerable continuity. It was found that many ore intercepts in adjacent holes, although of different elevations, were the same ore zone and could be mined as a continuous ore body. Up to this time lithologic information from drill holes was meager, especially since electrical resistivity or self-potential logging methods had not been used.

In late 1957, a new drilling program was commenced. These holes were logged not only for gamma radiation data but for resistivity and self-potential data as well.

It was recognized that with good resistivity data, ore horizons could be correlated in most cases within a few feet vertically. This was sufficiently accurate to be of great value in solving many immediate mining problems as well as correlating ore zones in preparation for long-range development.

In this area four separate ore zones were finally defined by surface drilling data and underground development work. The four zones are A, B, C, and D in descending order and are shown in Figures z, 3, 4, and 5, respectively.

Zone A, which was the uppermost zone, occurs in the upper part of the Westwater Canyon Sandstone near the Brushy Basin Shale. This zone strikes east-west over most of its length but swings to the southwest along the western edge. Zone A dips north from 5° to a maximum of 30°. This zone was developed and followed by drifts for 1900 feet along the east-west trend of which about the first B00 feet is shown here. This zone varies more than 20 feet stratigraphically.

Zone B, stratigraphically below Zone A, is generally along the southern border of Zone A. The strike of Zone B was just north of west and dipped to the north on an average of 5°. Zone B was considerably smaller in aerial extent than Zone A but elevationwise it extended approximately 20 feet above the lower edge of Zone A going down to just about the lowest limit of Zone A. Its limited distribution is such that it is not present in the cross sections A-A' and B-B' of Figures 6 and 7.

Zone C just below Zone B had a strike generally north of west, but swung slightly east of north in the western part. This zone dipped north about 9°. Stratigraphically this zone varied about zo feet from south to north; it was about the same elevation as Zones A and B on its southern edge but was somewhat lower than A and B on its northern edge. It may be readily seen that this zone, with some elevations about the same as Zones A and B and dipping under the other zones could complicate the interpretation of drillhole information. It could have been interpreted as more steeply dipping ore zones or nearly flat ore zones.

Zone D, the lowest zone in this area, was unusually long and narrow. Although Zone D had no clear-cut mappable features it followed a sinuous course in plan and had considerable bottom undulations which suggested that the ore fol-

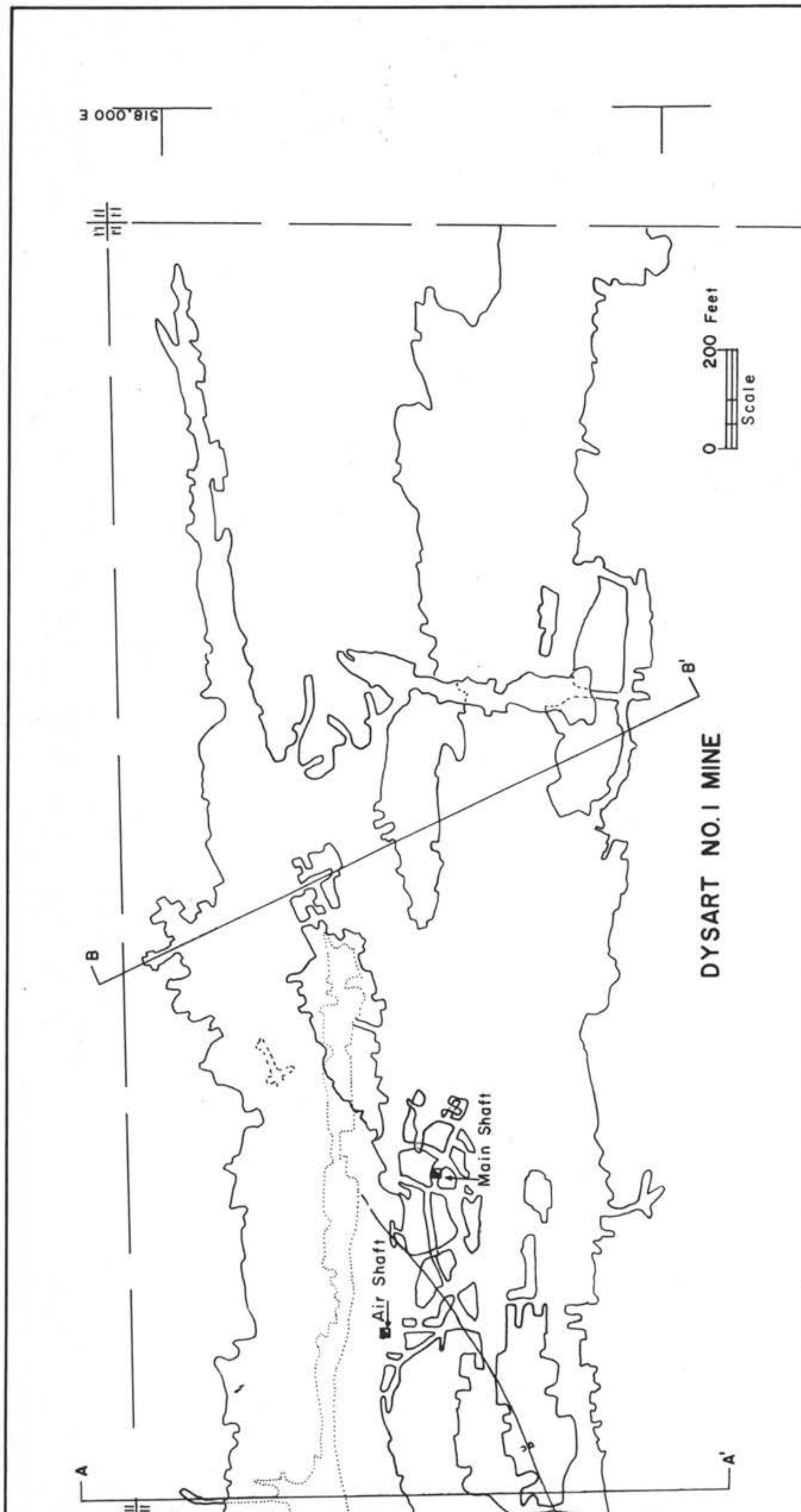


Figure 1

PLACE MAP OF THE DYSART NO. 1 MINE, MAIN WORKING. LOWER WORKINGS IN ZONE D SHOWN IN DOTTED OUTLINE.

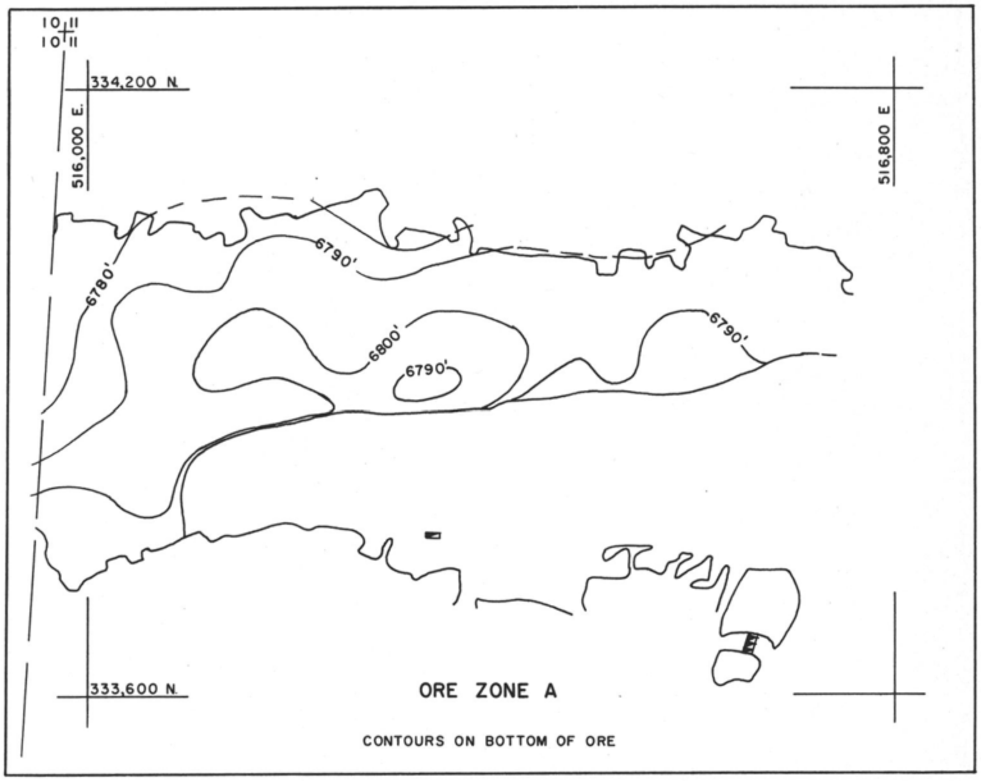


Figure 2

Plan map of ore zone A

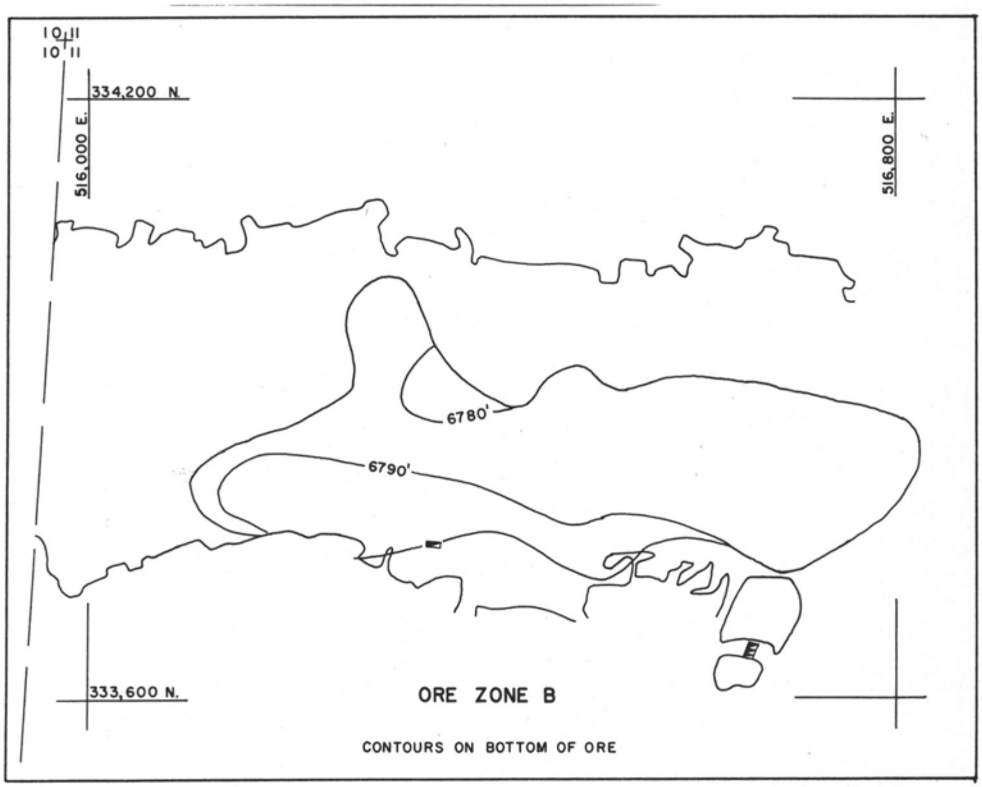


Figure 3

Plan map of ore zone B

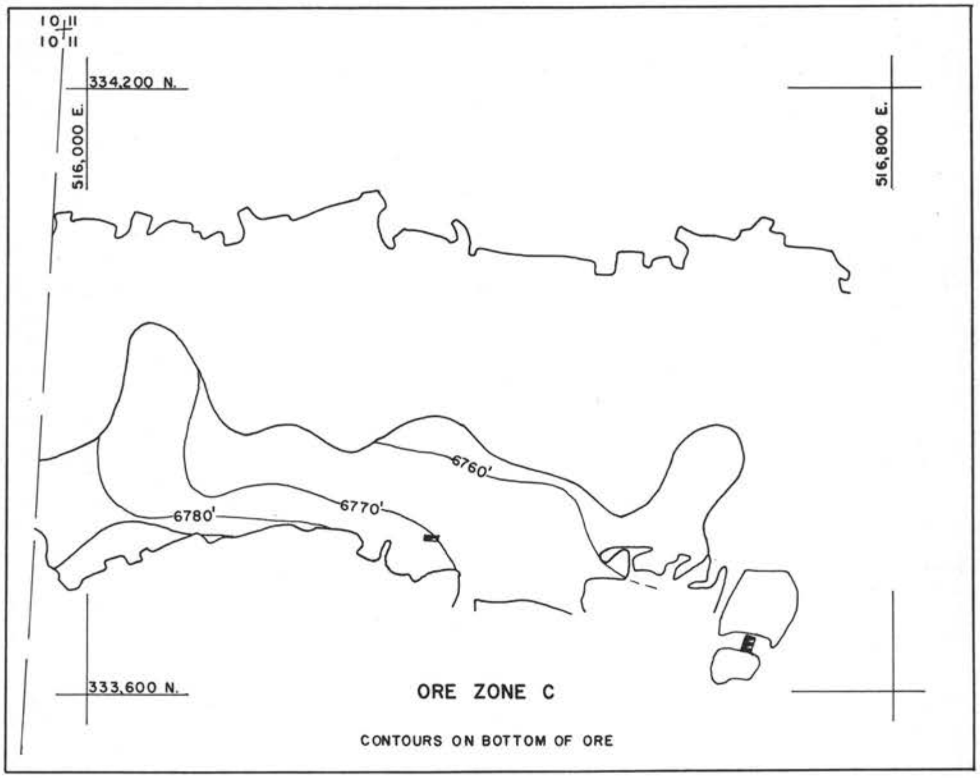


Figure 4

Plan map of ore zone C

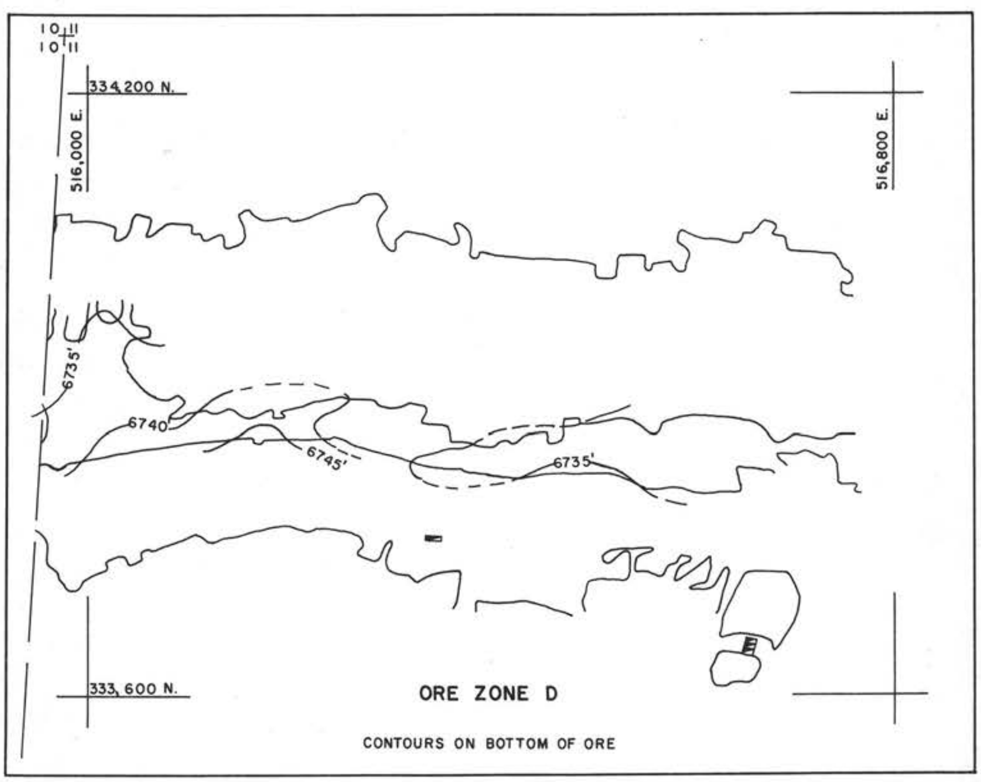


Figure 5

Plan map of ore zone D

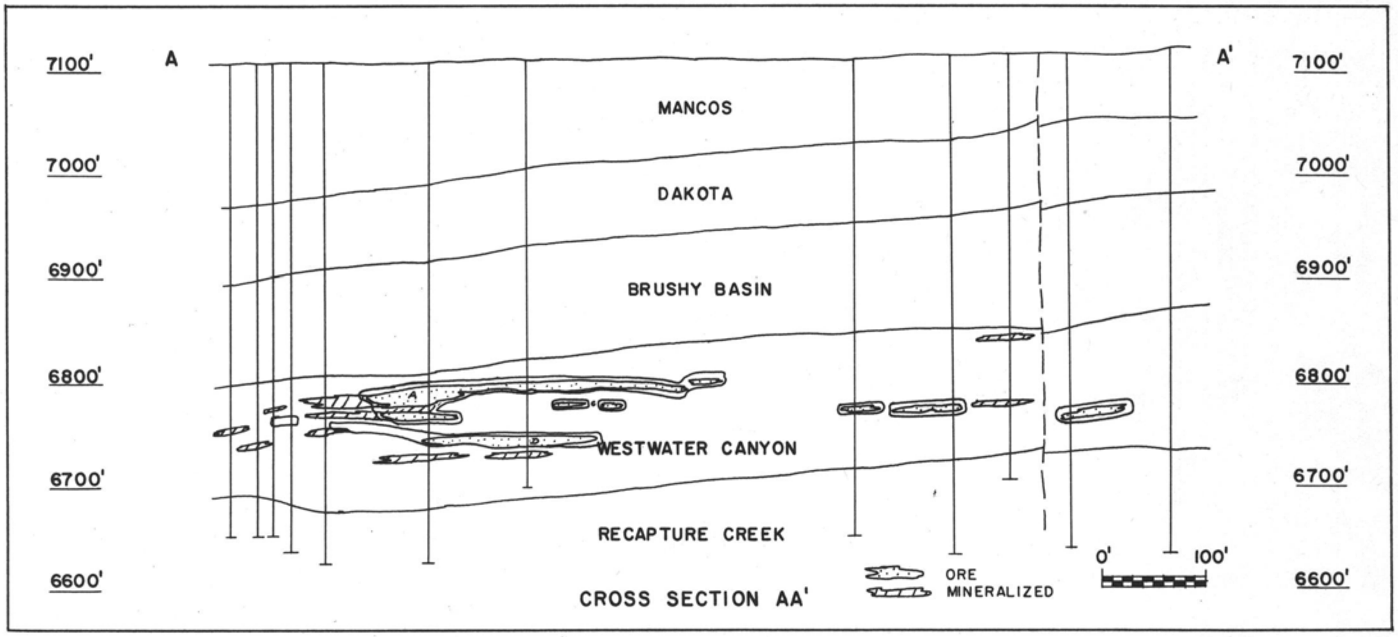


Figure 6

CROSS SECTION OF THE WESTERN SIDE OF THE DYSART NO. 1 MINE

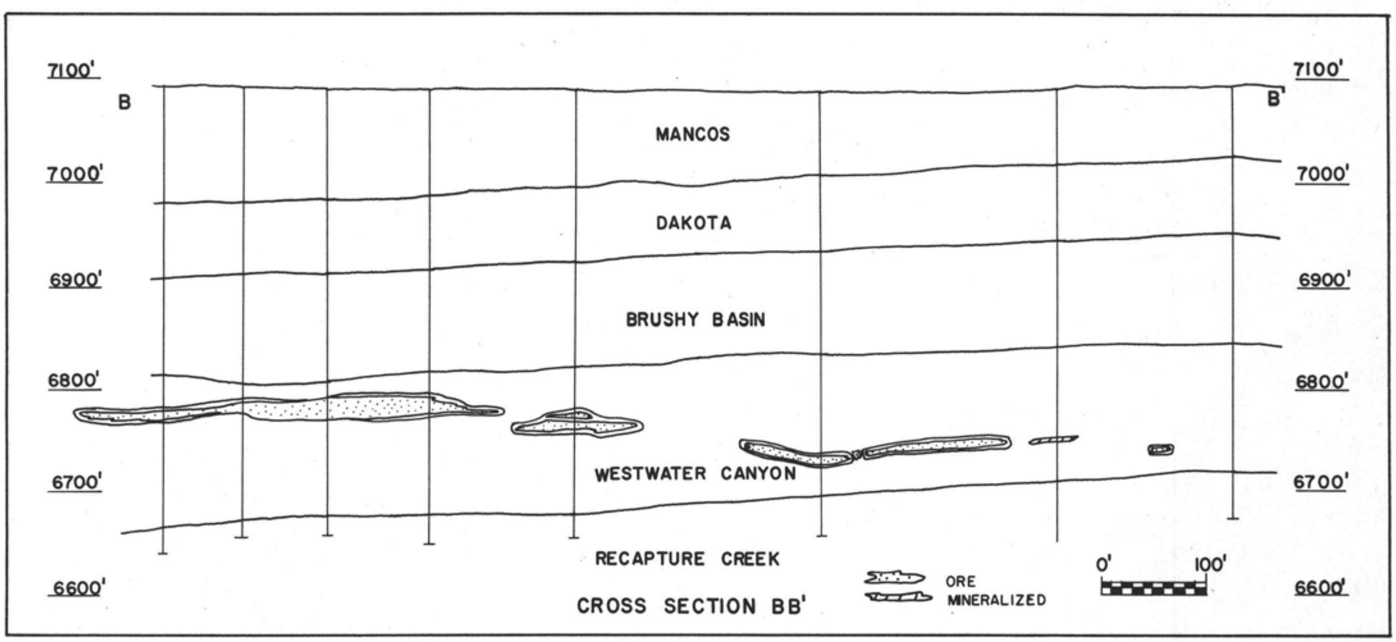


Figure 7

CROSS SECTION OF THE CENTRAL PART OF THE DYSART NO. 1 MINE lowed a sandstone channel. This zone is shown (dotted outline) in Figure I.

Cross section A-A (fig. 6) shows some of the thick ore occurrences that occurred in areas north and east of the main shaft. Cross section B-B (fig. 7) shows some of the thick ore occurrences that occurred in areas north and east of the shaft. The thick ore shown in the western half is the extension of Zone A, but the presence of exact equivalents of Zones B, C, and D in this area is uncertain.

There was only one major fault in the mine that had a considerable extent. This fault is shown in the southwestern area of the mine (fig. I ). It strikes northeasterly and dips to the southeast at a high angle. In the southwest the throw was estimated at ten feet or more, but as the fault was traced to the northeast the throw decreased. In the area northwest of the shaft the fault faded out and could not be traced farther. Underground observations, in few exposures where the fault crossed an ore zone, the ore was apparently faulted.

There were numerous exposures of festoon sedimentary structures. These had a gross west to east trend, in the direction of the mine workings. Therefore it would seem a natural conclusion that the direction of sedimentary transport was a factor in determining the trend and shapes of the ore bodies.

In detail the mineralization did not conform to sedimentary features. In some instances the ore followed bedding, and at other places cut sharply across the bedding at high angles with sharp ore-waste interfaces. In other instances the boundaries were gradational. Often the ore followed shale bands and erosion surfaces strewn with clay galls, but at other times there was no apparent bounding material.

# *Geology of the Homestake-Sapin Uranium Deposits, Ambrosia Lake Area*

WALTER GOULD, ROBERT B. SMITH, STEPHEN P. METZGER, AND PAUL E. MELANCON

## INTRODUCTION

The uranium deposits in sections 15, 23, and 25 provide indications of at least two ages of mineral implacement. It has also been osberved that location, configuration, and tenor of the ore pods are related to recognizable geologic features which may be used to assist in the planning and development of the mines. Specific features that have influenced the type and configuration of various occurrences include faulting, fracturing, and intraformational mudstones.

The deposits, discovered in 1955 by Sabre—Pinon Corporation, are at the western end of the Ambrosia Lake area in T. 14 N., R. 10 W., McKinley County, New Mexico. The mines are operated by Homestake—Sapin Partners, a partnership in which Homestake Mining Company is the general and operating partner and Sabre—Pinon Corporation the limited partner.

### STRATIGRAPHY

Uranium in commercially important quantities occurs throughout the vertical extent of the Westwater Canyon member of the Morrison Formation. The host rock is a fine-to coarse-grained, poorly to fairly well-sorted, massive and more generally cross-stratified, arkosic sandstone containing interbedded mudstone galls, seams, and layers. Color varies from gray through light yellow-brown to brick red.

Correlation of intraformational mudstones indicates at least five identifiable stratigraphic levels in which deposits can be found. The larger ore bodies are found near and above the middle of the member while thinner, more continuous, elongate deposits are characteristic of the lower portion. An obvious relationship between the ore deposits and specific sedimentation features has not been established.

### STRUCTURE

Structural features that may have influenced uranium localization on the Homestake—Sapin properties include the Ambrosia dome, a related easterly plunging syncline, and north- and northeasterly striking fault sets (fig. ).

The west flank of the Ambrosia dome lies in section 15 and is responsible for the steep dip of the section 15 deposits. The east-southeasterly striking axis of the related syncline extends across the southern half of section 23. These structures were considered by Zitting et al. (1957) to have had considerable influence in localizing uranium deposits in the Ambrosia Lake area.

Faults and fractures have influenced either directly or indirectly the localization of ore deposits on the Homestake-Sapin properties. Areas of increased fracture density within the ore bodies show evidence of uranium removal while other fracture areas have apparently aided in the localization of the ore.

## ORE DEPOSITS

There are two basic types of ore occurrence that make up the Homestake—Sapin ore bodies. A continuous, elongate, thin layer of ore that has been deposited about parallel to the bedding and trends more or less parallel to the west to east direction of sedimentation is referred to as trend-type ore. Dimensions of these deposits range from a few tens of feet to several hundred feet in width and from a hundred feet to more than two thousand feet in length. The thin, continuous band ranges from less than one foot to more than five feet in thickness. Greater thickness is found where the band crosses the bedding and abruptly changes elevation (fig. 2). These thick occurrences in the band, called rolls, have been found to occur at predictable intervals across the trend of the deposit, and their elongation or trend direction is parallel to the long dimension of the deposit in which they occur.

The second type of ore occurrence, called a stack, is a very thick, more or less equidimensional deposit. The trend or long direction of these deposits is generally at an angle to the trend direction of the area and quite frequently parallels the strike of the associated fracture system.

The trend deposits generally appear to be the oldest ore in the mines and correspond to Granger et al. (1961) prefault ores. Most of the stack deposits are the result of vertical and horizontal redistribution of older trend deposits along zones of increased permeability.

Factors that may affect permeability and thus influence the localization and configuration of a stack deposit include increased fracture density, abrupt changes in the grain size and sorting of the host rock, and the presence or absence of intraformation mudstone layers.

More than one age of redistribution of the uranium appears to be present, and, in fact, it is likely that redistribution may have been a continuing process related to fluctuating hydrostatic pressures, ground-water levels, and changing chemical properties of the formation waters. Indications of a changing chemical environment include the presence of oxidized and unoxidized ores within a few feet of each other and the increasing amount of vanadium found in what are almost certainly younger ores.

After the initial deposition of trend ores in a reducing environment, oxidizing solutions began to invade the area, taking uranium into solution and transporting it until a suitable environment for reprecipitation was encountered. The present location and configuration of some of the deposits provide excellent evidence of this changing environment.

The zone of changing environment, referred to as the reaction zone, extends from the barren, oxidized red sandstone through the mineralized, unoxidized rock to the barren unoxidized sandstone. This zone may vary in width from a few feet to several hundred feet.

Various examples of the basic occurrences and their appar-

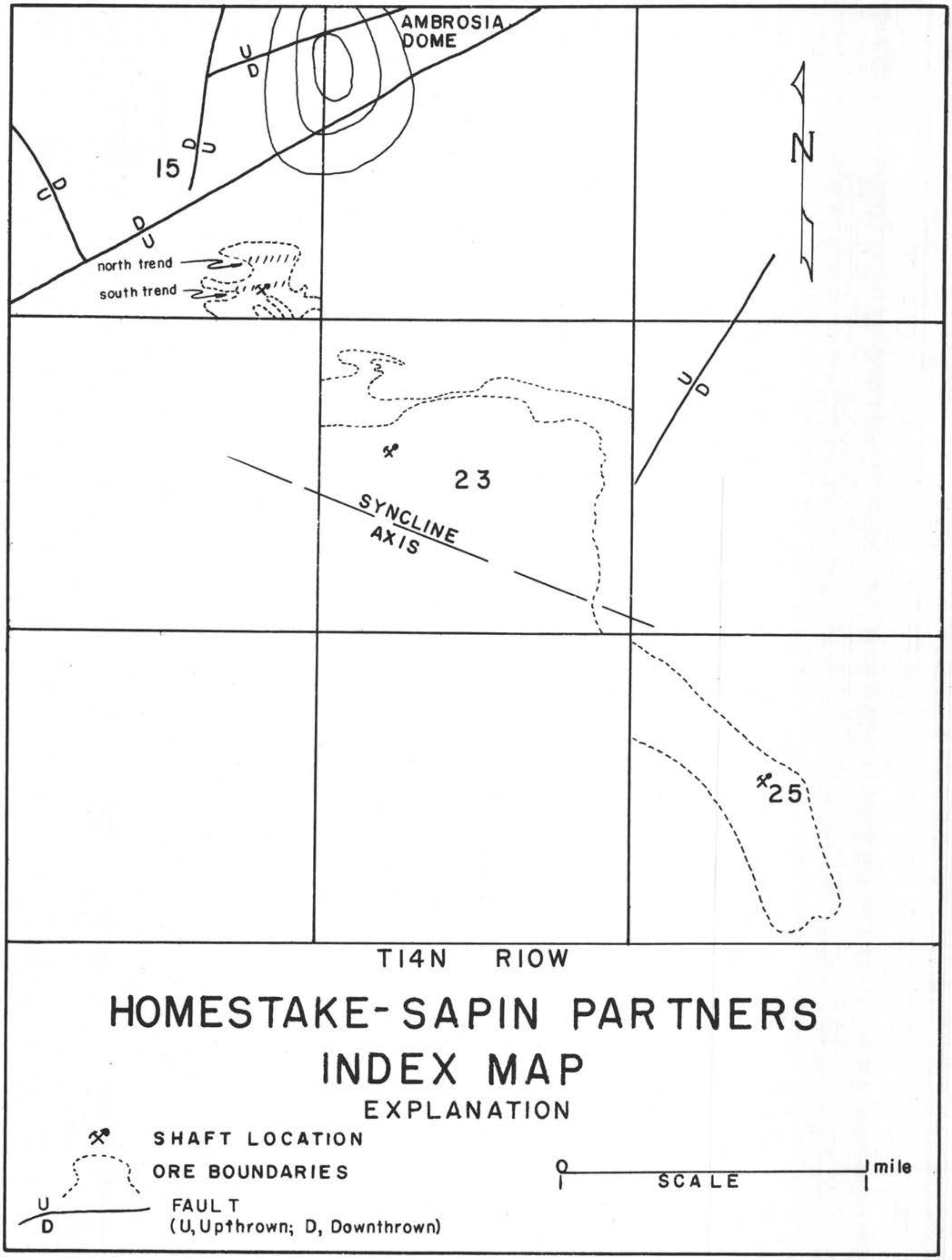


Figure 1

INDEX MAP OF THE HOMESTAKE–SAPIN URANIUM DEPOSITS


Figure 2

CROSS SECTION OF THE HOMESTAKE–SAPIN SECTION 23 MINE SHOWING RELATIONSHIP OF TREND AND STACK ORE BODIES ent relationship to each other and associated geologic features are presented for each of the Homestake—Sapin properties.

## SECTION 15

The section 15 ore bodies are in the southeast quarter of the section extending 1200 feet north and 1700 feet west from the south and east section lines. They are contiguous with the Kermac Nuclear Fuels section 22 ore bodies to the south, and together seem to represent the western extremity of the southern Ambrosia Lake depositional trend.

The deposits occur in various stratigraphic units from 20 feet above the base of the Westwater to the Poison Canyon "tongue," and because of their location on the southern flank of the Ambrosia dome, dip 7 to 12 degrees to the southwest.

There are two well-developed areas of trend deposition in section 15 separated by a barren area some 200 feet in width. The southern band extends 1800 feet in a S. 70 W. direction from the east section line and is paralleled by a northern band that is about 700 feet in length (fig. I ). Rolls in these trend deposits appear to be spaced 120 feet apart; one has been traced the entire length of the deposit.

Most ore, however, occurs in stack deposits. An excellent example of a stack resulting from redistribution is found in the west-central part of the mine. Here a thick, high-grade ore body has been localized along fractures. The stack ore is definitely younger than an overlying roll of trend ore and appears to have been derived from a westward extension of the older ore.

A different form of stack deposit can be seen in the northern part of the mine. Here, a large reworked ore body has been built along the northeast edge of what appears to have been an advancing oxidizing environment. The deposit is essentially tabular, averaging 25 feet in thickness, and dipping slightly more to the southwest than the enclosing host rock. At the updip or northeast extremity, the ore abruptly increases to a thickness of more than 5o feet. The presence of a moving oxidizing environment is suggested by buff-colored sandstone that occurs above the thinner more uniform part of the ore body and immediately downdip from, but not penetrating or overlying, the thick stack development; the ore is completely underlain by gray sandstone.

The vanadium content of section 15 ores is nearly double that of the other ore bodies. It is universally associated with the redeposited ores and is probably present to a lesser degree in the older ores. The concentration of vanadium also appears to be a function of the stratigraphic position of the ore; higher vanadium values prevail in the upper units of the Westwater Canyon. Accessory minerals found are calcite, barite, and native selenium. Calcite is present in nearly all the ore; barite is rare and only in fractures; and selemium occurs as gray and red native selenium and as the mineral ferroselite (Granger et al., 1961). Gray elemental selenium is always found along the contact zone between buff and gray sandstone and in fractures. The red variety occurs as an efflorescent coating on the mine walls and is associated with all types of occurrence.

## SECTION 23

The section 23 ore deposits extend the entire width from west to east across the northern half of the section and con tinue to the south along the eastern boundary (fig. 1). Ore bodies have been found throughout the vertical extent of the Westwater Canyon Member in section 23; the major deposits occur near the middle of the member.

The older, trend ore in section 23 ranges from 1200 feet wide at the western end of the ore body to about 8o feet wide near the center. The distance between rolls in the trend ore varies from i00 feet in the west end of the mine to 5o feet in the eastern end. Individual rolls have been followed for 800 feet along the N. 7o W. strike direction. The ability to predict the position of rolls has aided in planning underground exploration and mine development.

The molybdenum minerals, ilsemannite and jordisite (Granger et al., 1961) are commonly found underlying the ore and particularly in the bottom part of the rolls in the west end of the mine.

Thin ore bodies and streaks of mineralization, in the same horizon as known ore, have been penetrated by surface drill holes in the southern half of the section, a fact which appears to indicate that the older ore may have extended over a considerably larger area than it presently occupies. Thus, it is quite probable that uranium now contained in the thick stacks was derived from previously existing trend deposits which were dissolved, transported updip to the north, and redeposited within the reducing portion of the reaction zone.

Specimens from the reaction zone show the sharp transition from unoxidized gray rock, rich in pyrite, to buff and then red sandstone where the pyrite has been completely oxidized to limonite and hematite. Larger buff zones are found in areas of increased north-south fracture density. It is also in these areas of increased permeability that the largest redistributed ore bodies are found. In section 23, these secondary deposits may be 120 feet thick, 200 feet wide, and extend for 700 feet along the reaction zone.

The effect of an extreme increase of permeability caused by a conjugate joint system can be seen in the southwest part of the mine. The depositional pattern is erratic and shows definite indications that ore has been dissolved from areas where solutions could move freely and be redeposited in nearby areas where flow may have been restricted by the intersection of fractures. This process results in triangular-shaped, high-grade ore bodies.

A system of east-west fractures, normal to the northerly direction of redistribution, is dominant near the center of the ore body. The resulting secondary deposits are as much as 7o feet thick, as narrow as 5o feet, and 500 feet long. The stacks were apparently built up along the plane of the fracturing by an increased flow of the uranium-carrying solutions as well as the damming effect of gouge along the fracture surfaces (fig. 3).

The position of the reaction front, in the vicinity of a large fault in the eastern part of the mine, has changed from over the ore on the west side of this fault to under the ore on the east side. The fault strikes N. 3o W. and has a vertical displacement of about 25 feet. The change seems to result in the deposition of thinner, wider, more continuous ore bodies which spread over the reaction zone rather than develop thick, narrow ore bodies under the reaction zone to the west of the fault.

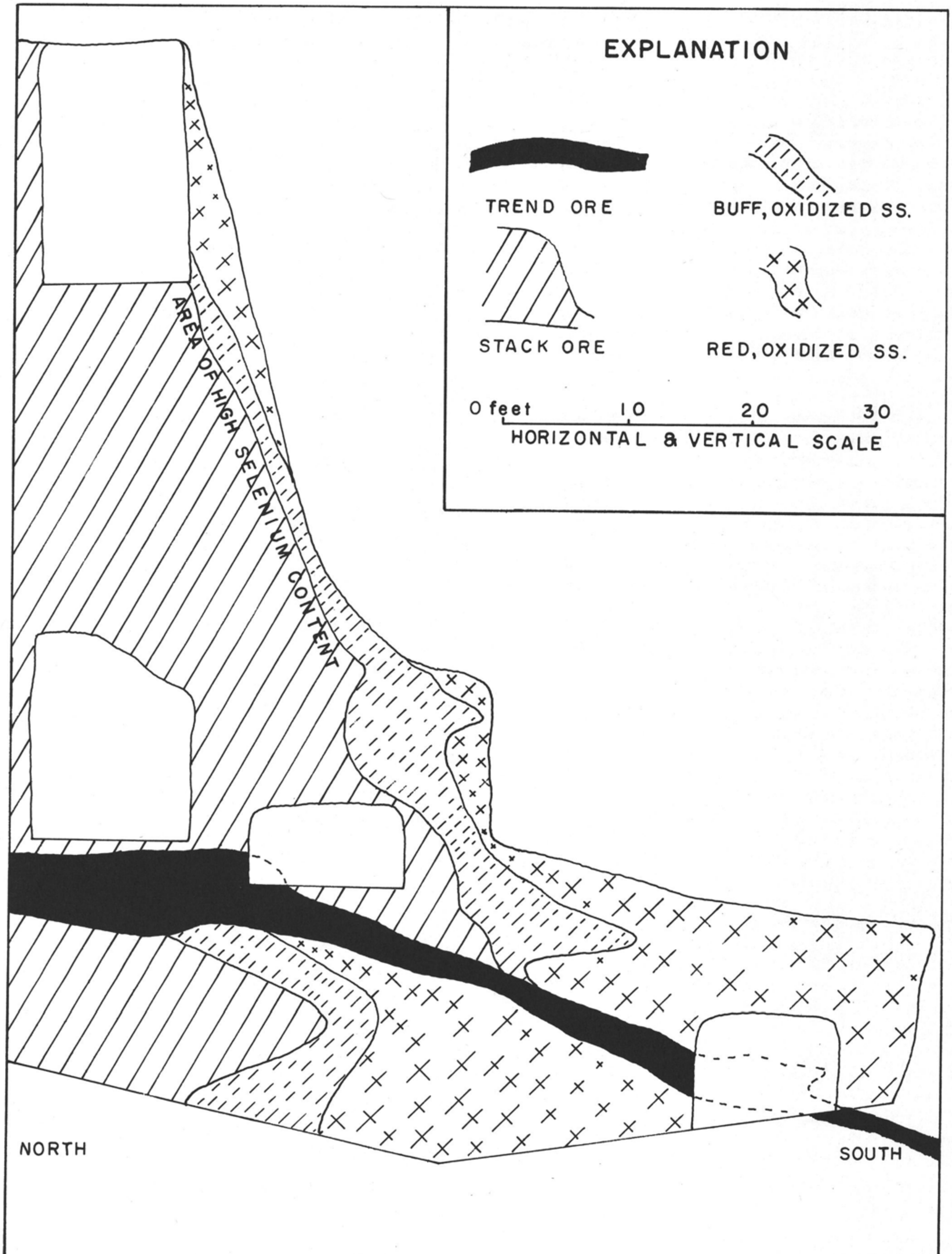


Figure 3

CROSS SECTION OF THE BOUNDARY ZONE BETWEEN ORE AND OXIDIZED SANDSTONE

## SECTION 25

The section 25 ore deposit is 5800 feet in length and 300 to 1200 feet in width, strikes northwest-southeast, and occurs as a series of interconnected or isolated lenses, pods, and trends, large and small throughout the vertical extent of the Westwater Canyon Sandstone.

The ore in which the mine is being developed is 1000 feet south of the northwest section corner and extends in a southeasterly direction to the central part of the section where the direction of strike changes to S. I 5 E. until it crosses the south section line.

Deposits in the basal units of the Westwater Canyon are characterized by trend ore. In the trend ore, the strike of the rolls is east-west, the rolling effect occurring in various magnitudes of pitch or roll, some very gentle and others almost overturned. An increase in grade is usually associated with the roll.

Section 25 presents definite evidence that fracturing occurred after the trend ore was deposited, thereby providing more permeable zones through which oxidizing solutions traveled. These solutions removed uranium from the already deposited trend ore and carried it along the more permeable zones until conditions were again suitable for redeposition. The distance the uranium has been carried may vary from a few feet to as much as a mile.

Ore of the 7 north stope represents secondary deposition in such a fracture zone, mineralization occurs as a high-grade mass ranging in thickness from 5 to 15 feet. It consists primarily of coffinite, with assays running well above one percent. The ore is controlled by northwest-southeast striking reverse faults and associated joints, dipping 6o° S., which all have about two feet of displacement. Although the bulk of the uranium occurs along the fractures, ore is also disseminated in the surrounding rock.

Structural control of redeposition has provided a means of locating new and unsuspected ore pods. This is done by the projection of the strike of the fractures from an area of known ore occurrence to a previously unexplored area. Uranium from the trend deposits has apparently been taken into solution by formational waters migrating downdip, leaving what appears to be an insoluble black residue. Some workings show the skeletal remains of the original trend ore and its associated rolls. Exploration downdip and diagonal to the strike of the fractures has located considerable masses of black ore.

Section 25 provides conclusive evidence that secondary redeposition was controlled in large part by northwest-southeast fractures particularly where they intersect a roll in the trend ore. Equally strong evidence also shows that fracturing had nothing to do with controlling the deposition of east-west trending rolls.

In the 74 west area, trend ore has been subjected to redistribution through intense fracturing. Increased permeability due to the fracturing has enabled solutions to redistribute uranium vertically, forming stack ore ranging in thickness from 4o to 110 feet. In the southeast part of the mine these thick stacks appear to include mineralized beds connected by mineralized fractures forming nearly vertical masses of medium-grade ore, 0.20 to 0.3o percent U308. In the 23 east stope, redistributed ore lies nearly parallel to the bedding. Here the uranium-rich solutions were apparently confined vertically by impermeable mudstone beds.

Redistributed mineralization accounts for the greatest ore tonnage in section 25, some stack ore bodies reaching more than l00 feet in height and from 5o to 300 feet in width. In many instances, remnants of the original trend ore can be identified in association with the redistributed stack ore.

The Section 25 mine is one in which the relationship of local structure to the position and configuration of known or suspected ore bodies has played and will continue to play a major part in the exploration and exploitation of ore.

## CONCLUSIONS

Reoccurring geologic features that are a part of or associated with the Homestake—Sapin uranium deposits have been recognized and are being used to plan underground exploration and development.

The most prominent guides that can be used in these programs include (I) the predictable interval between rolls in trend deposits; (2) redistribution of trend ore downdip along fracture zones that intersect the trend; and (3) the abrupt color change associated with the reaction zone.

## REFERENCES

Granger, H. C., Santos, E. S., Dean, B. G., and Moore, F. B. (1961) *Sandstone-type uranium deposits at Ambrosia Lake, New Mexico—an interim* report, Econ. Geol., v. 56, n. 7, p. 1179-1209.

Zitting, R. T. et al. (1957) *Geology of the Ambrosia Lake area uranium deposits, McKinley County, New Mexico,* Mines Mag., v. 47, p. 53-58.

# *Geological Setting of an Anomalous Ore Deposit in the Section 30 Mine, Ambrosia Lake Area*

T. A. CLARY, C. M. MOBLEY, AND G. F. MOULTON, JR.


## ABSTRACT

Two of the largest ore bodies in the Ambrosia Lake area lie in sections 29 and 3o. These ore bodies are one above the other in the "A" and "B" sandstones in the upper Westwater Canyon Member of the Jurassic Morrison Formation.

The principal ore mineral is coffinite which has been precipitated by a vegetal derivative termed carbonaceous material.

Folding and faulting during upper Westwater Canyon time caused local changes in stream direction, created an environment suitable for vegetal growth and burial, and the deposition of thick sand lenses.


## INTRODUCTION

The Section 3o mine is operated by Kermac Nuclear Fuels Corp. and lies in the Ambrosia Lake area, McKinley County, New Mexico (fig. ). The vertical shaft is 75o feet deep and the mine has over 3o miles of workings on three operating levels. Since production began in 1958 more than one million tons of uranium ore have been produced from the two upper Westwater Canyon ore bodies.

The Ambrosia Lake area has three major subparallel, northwest-striking ore trends. Figure 1 shows the middle and southern trends converging on sections 29 and 3o. The high concentration of uranium at this junction has been a controversial subject since its discovery. This paper describes and explains some of the ore characteristics and their relationship to structure and sedimentation.

## GEOLOGICAL SETTING

The Section 3o mine lies about three miles southeast of the Ambrosia dome. The area occurs at the juncture of the middle and southern ore trends (fig. ). These southeasterly trends are comprised of numerous subparallel ore bodies, which follow the alignment of current lineations.

The middle member of the Jurassic Morrison Formation, the Westwater Canyon, is composed of lenses of arkosic sandstone interbedded with shale. Four sandstone and three shale units can be correlated in sections 29 and 3o (figs. 2, 3). In addition to these persistent units, there are many discontinuous shale lenses and mudstone conglomerates.

## ORE DEPOSITS

The "A" deposit is composed of intersecting irregularly crescent-shaped ore bodies. The axes are plotted in Figure 4. The shaft lies north of the intersection and in the concave part of both. The ore bodies range from 100 to 600 feet in width and from three to 60 feet in thickness of the ore bodies are shown in Figure 4. The grade ranges from 0.15 percent to over 5 percent $U_3O_8$. Selected samples taken near logs are as high as 15 percent. This is the largest known sandstone ore body in the district.

The "B" deposit is an isolated irregular tabular mass lying beneath the "A" ore body (fig. 5). It ranges in thickness from three to 4o feet, is the largest known "B" ore body in the district, and is separated by a minimum of one mile from other "B" deposits.

The southern trend shown in Figure 1 is composed primarily of "C" and "D" ore. Inasmuch as deposits in these sandstones are present in the subject area, they are minor in comparison to the upper ore and will not be discussed (fig. 3).

The principal ore mineral has been identified as coffinite $(U(SiO_4)_{1-x}(OH)_{4x})$. The uranium is associated with carbonaceous material derived from plant debris (R. G. Corbett, written communications). The black ore probably owes its color to the carbonaceous material that coats the sand grains. Where the ore is abundant the pore spaces in the sandstone are filled.

The long dimensions of the ore bodies usually parallel the directions of depositional trends. The ore layers within a deposit display a variety of irregularities. They may split and occupy two horizons or may abruptly plunge to a lower horizon and transgress intraformational disconformities.

Fossiliferous chert, vein quartz, obsidian, and highly strained quartz fragments have been observed in thinsections. The main authigenic minerals include silica, calcite, and clay with lesser amounts of pyrite, gypsum, barite, and hematite. Alteration of feldspars is mainly predepositional.

## RELATIONSHIP TO STRUCTURE AND SEDIMENTATION

The "A" and "B" ore is trapped in a horst block between two north-striking faults. Although the east boundary fault has less than ten feet of displacement it tends to confine the ore to the upthrown block. To the south, the fault dies out and is lost in a fracture zone and has no control over the ore. The west boundary fault displaces the "A" ore about 20 feet. The ore on the upthrown block is thick and massive, whereas the ore in the downthrown block is in discontinuous pods. The "B" ore does not extend to the west boundary fault (figs. 4, 5).

Measurements of current lineation and log orientation in the "A" sandstone show that the stream direction in the section 3o area was different from the regional direction. Figure 4

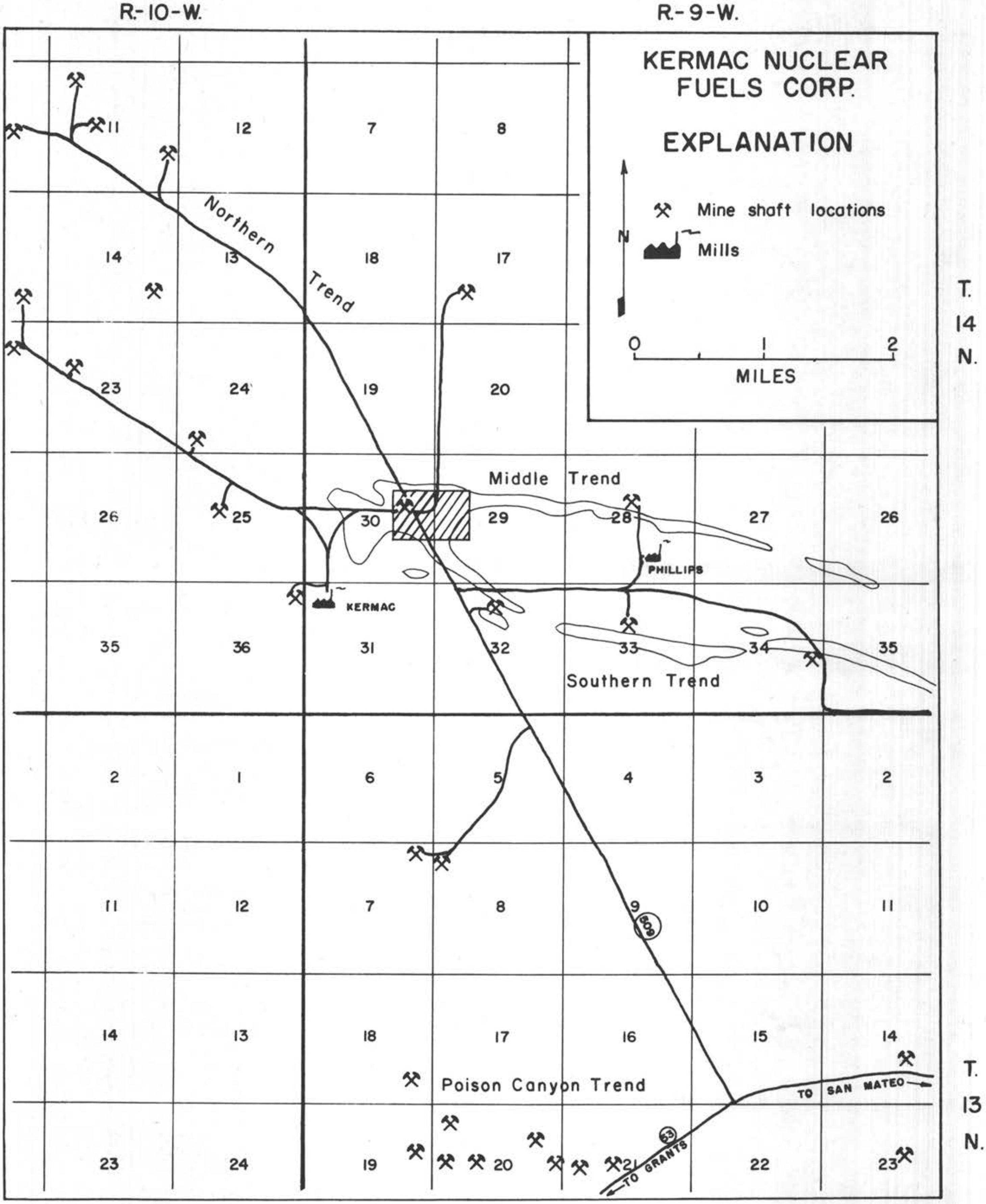


Figure 1
LOCATION MAP OF PART OF THE AMBROSIA LAKE AREA

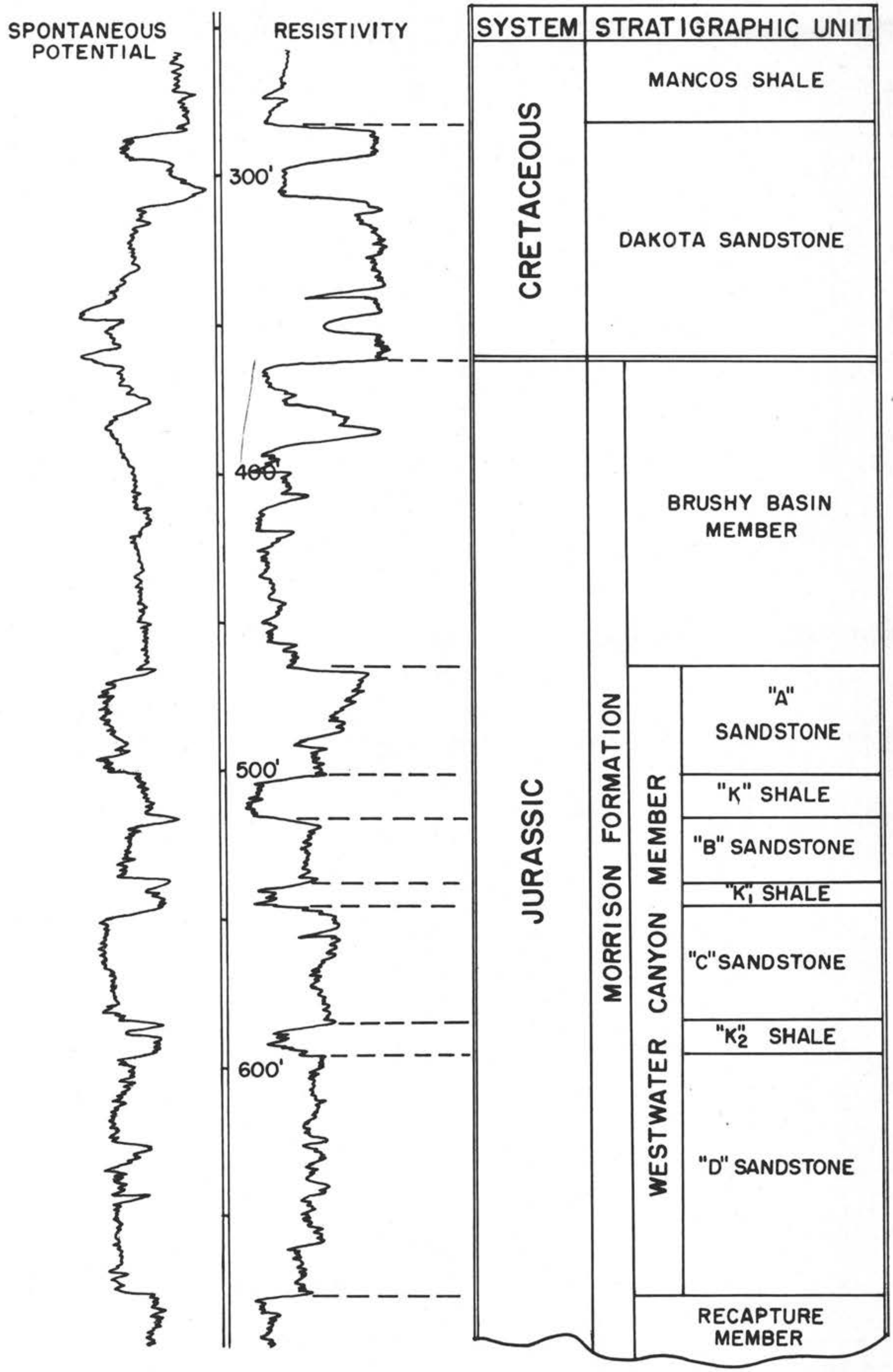


Figure 2

SPONTANEOUS POTENTIAL AND RESISTIVITY LOGS OF A DRILL HOLE SHOWING DIVISIONS OF WESTWATER CANYON MEMBER

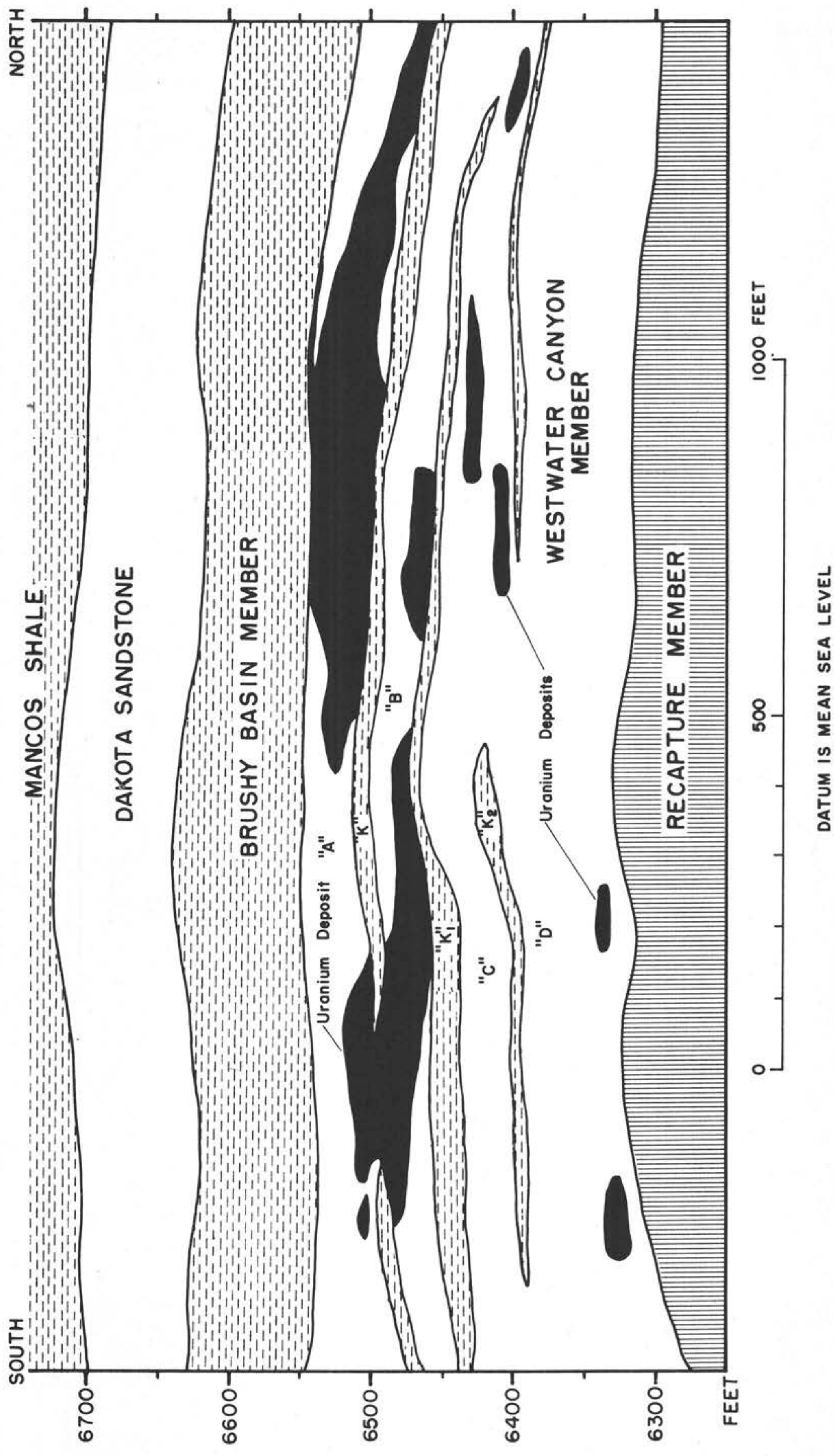


Figure 3

Diagrammatic geologic section showing the relationship of the uranium deposits to the stratigraphic units

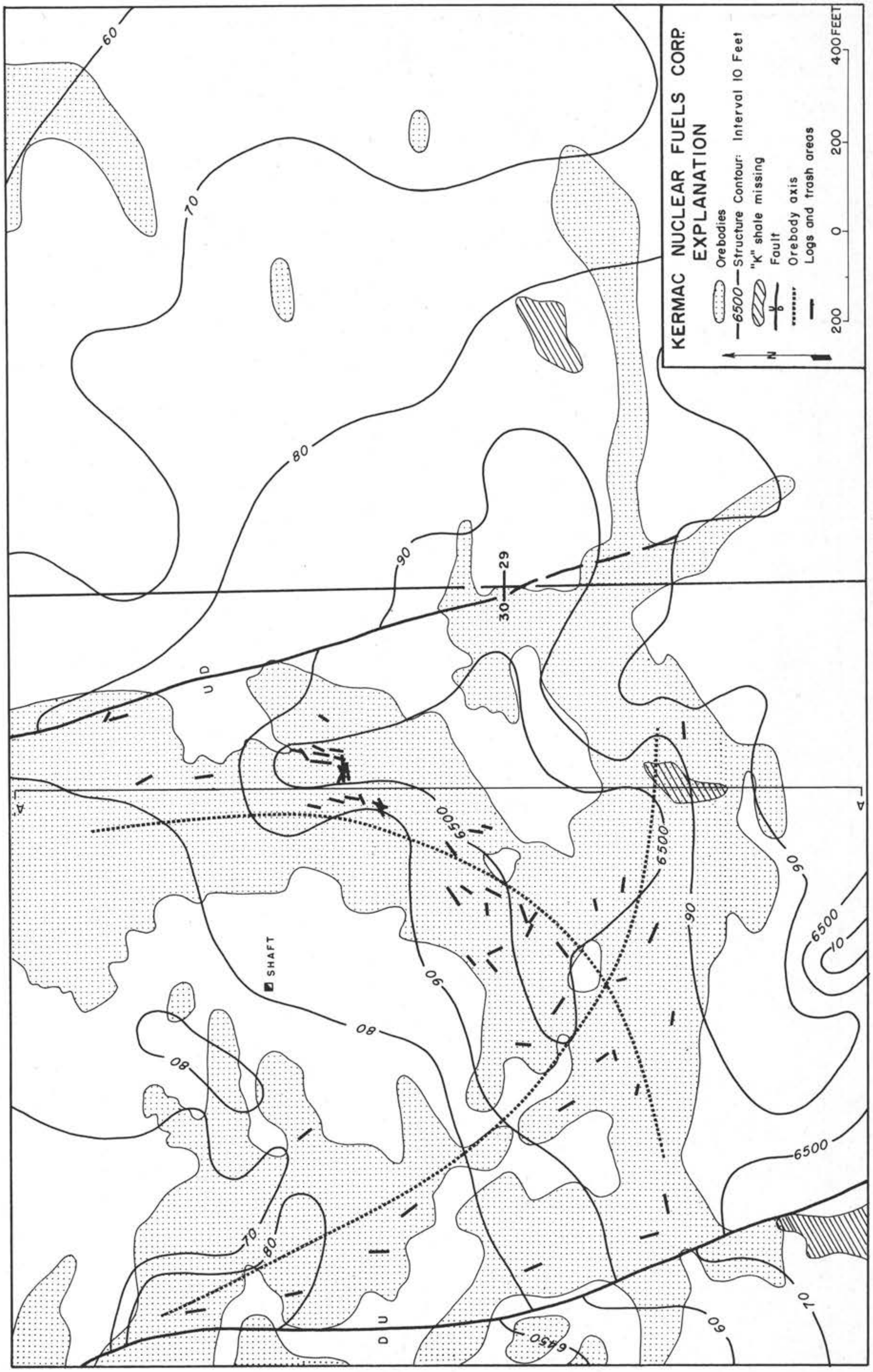


Figure 4

STRUCTURE CONTOUR MAP ON TOP OF THE "K" SHALE AND ORE BODIES IN THE "A" SANDSTONE

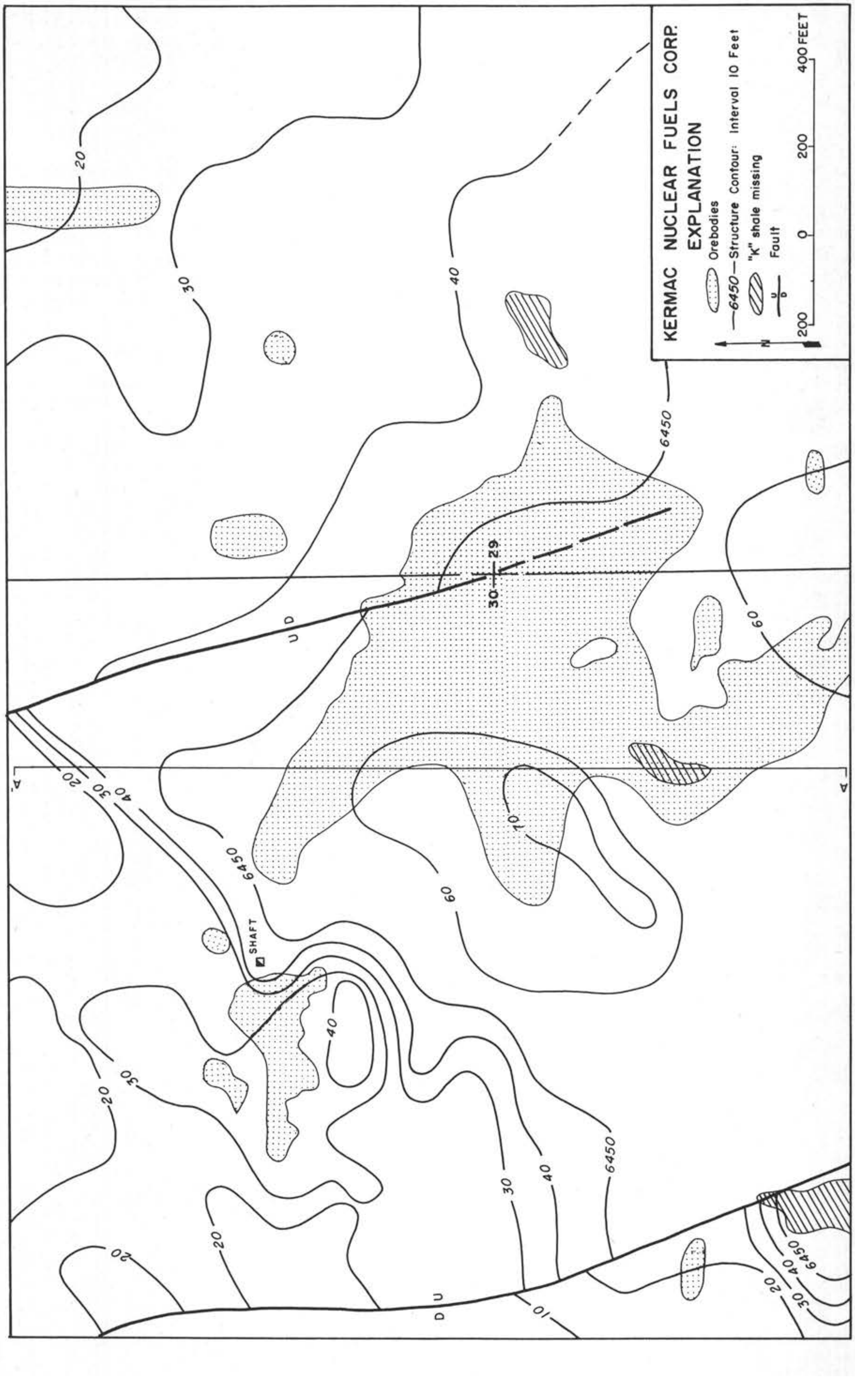


Figure 5

Structure contour map on top of the "$K_1$" shale and ore bodies in the "B" sandstone shows the axes of the crescent-shaped ore bodies. The current lineation also conforms to these axes. The axis of the eastern crescent is east-west in the southwestern part of the area and swings north of the structural high to south of the shaft and then parallels the north-striking east boundary fault. The axis of the western crescent parallels the north-striking west boundary fault in the northwestern part of the area and then swings east and conforms to the regional direction.

Deposition of the Westwater Canyon was continuous and followed a normal sequence into the Brushy Basin Shale. The strata from the "$K_1$" shale through the "A" sandstone are transitional. The isopach map of the "B" sandstone illustrates a cut-and-fill type of deposition with mud and silt being deposited to the southeast and thick sand in the northwest (fig. 6).

Deposition of the "A" sand was interrupted by intermittent folding and faulting which disturbed the surface enough to cause erosion through the "K" Shale and deflection of the streams parallel to the faults. Stream congestion and flooding caused numerous mudstone conglomerates to be deposited and created a local environment suitable for dense vegetal growth.

## RELATIONSHIP TO VEGETAL MATTER

Fossil vegetal matter is abundant in the "A" sandstone and is sparse in t e "B" sandstone. Some areas containing vegetal matter are mineralized whereas other areas are barren. However, the ore is always associated with carbonaceous material. The "B" sandstone did not contain enough vegetal matter to produce the amount of carbonaceous material present.

The decomposition and fossilization of the vegetal matter produced water-soluble humic compounds. The humic charged ground water in the "A" sandstone was protected by faults creating stagnation and allowed the ore-controlling humic acid material to split into different horizons, transgress intraformational disconformities, and move into the "B" sandstone through a hole in the "K" shale (figs. 4, 5). Later the humic matter was precipitated and partly filled the pore spaces and coated the sand grains.

When mineralizing solutions were introduced, only the host rock containing carbonaceous material was favorable for uranium mineralization. Therefore, the carbonaceous material is the true ore control and vegetation is its source.

This interpretation explains the sheetlike configuration and superposition of the "A" and "B" ore bodies as contrasted to the extremely long, narrow ore bodies found in the lower West-water Canyon.

## CONCLUSIONS

The striking feature of the Section 3o ore deposits is that the largest and highest grade "A" and "B" ore bodies in the upper sandstones of the Westwater Canyon Member of the Jurassic Morrison Formation in the Ambrosia Lake area are superimposed at the juncture of the two district ore trends.

Folding and faulting affected local deposition of the sandstones and shales creating an environment for lush vegetal growth. These two exceptional ore bodies are confined between two faults and are continuous through a hole in the impervious "K" shale.

Humic matter derived from fossil plant debris in the "A" sandstone was trapped by faulting. Vegetal matter was sparse in the "B" sandstone and the hole in the "K" shale offered a logical passage for humic matter to be introduced from the "A" sandstone.

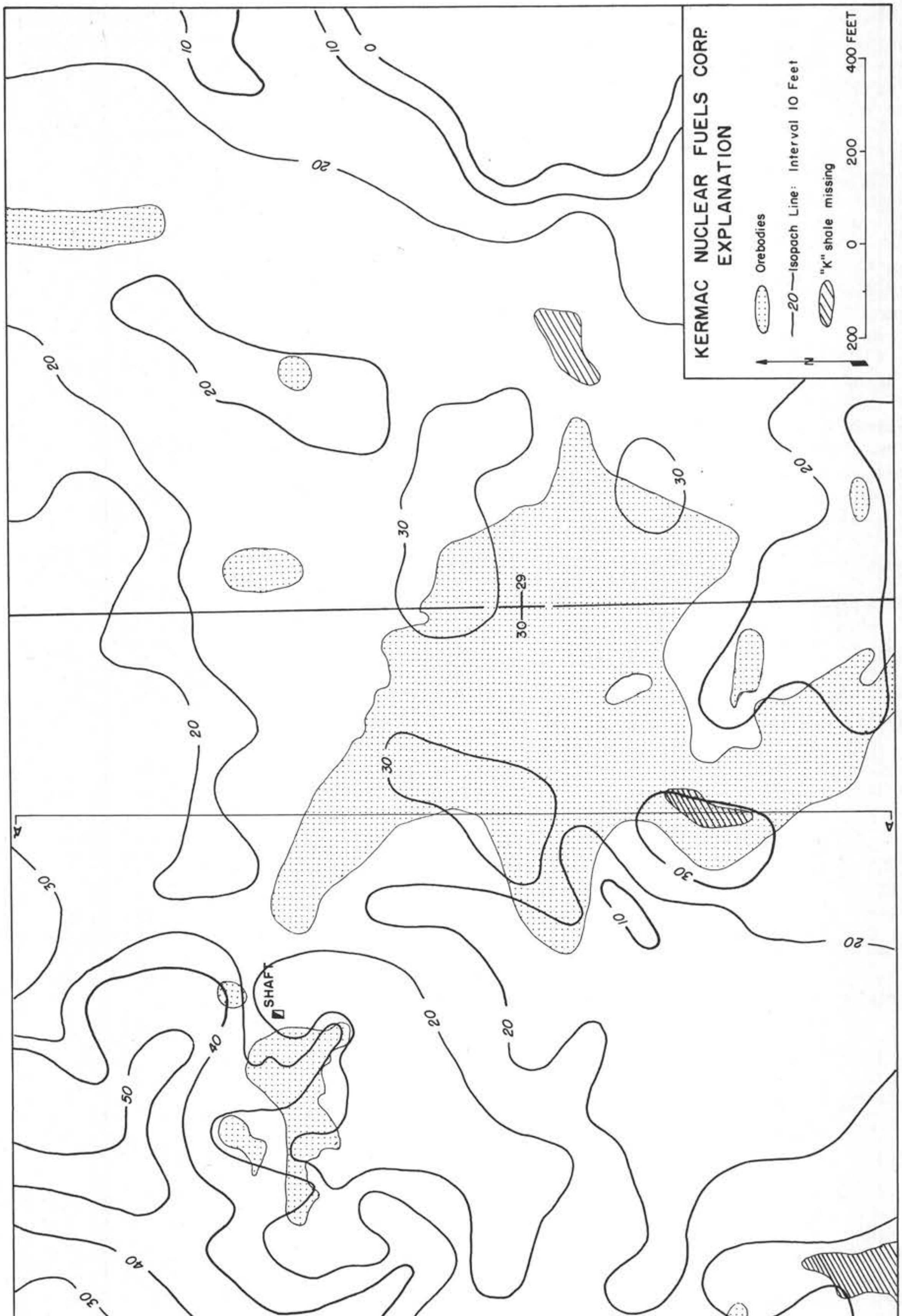


Figure 6

ISOPACH MAP OF THE "B" SANDSTONE AND ORE BODIES IN THE "B" SANDSTONE

# *Uranium and Vanadium Minerals Occurring in Section 22 Mine, Ambrosia Lake Area*

R. G. CORBETT

## INTRODUCTION

This paper considers the occurrences and identification of several uranium and/or vanadium minerals at the Section 22 mine in the Ambrosia Lake area. The results contained herein are extracted from a longer manuscript that is in preparation.[1]

The writer has positively identified ten uranium and/or vanadium minerals from the mine, and there is good reason to believe that at least two more are present. This rather broad suite of minerals reflects processes which have affected an originally low-valent mineral assemblage.

Table i summarizes the uranium and/or vanadium minerals occurring in the mine. The table uses two parameters to describe the associations: ( 1) the physical character of the occurrence (coating or filling fracture) and (2) the relative valence of the uranium and/or vanadium in the mineral.

TABLE 1. URANIUM AND/OR VANADIUM MINERALS OCCURRING IN SECTION 22 MINE

The writer has identified all minerals (except those which are followed by a symbol) by X-ray diffraction.

PHYSICAL CHARACTER OF OCCURRENCE

| Valency | Disseminated within sandstone | Replacement of sandstone | Coating or filling fracture | Encrusting mine workings |
|---|---|---|---|---|
| Low | coffinite<br>uraninite<br>montroseite | uraninite | uraninite<br>montroseite | |
| Intermediate | paramont-<br>roseite<br>corvusite [a] | | paramont-<br>roseite<br>doloresite | |
| High | tyuyamunite | | tyuyamunite<br>metatyuya-<br>munite<br>carnotite [b] | pascoite<br>bayleyite<br>andersonite |

[a] indicated identification by color and position in sequence.
[b] indicates mineral reported by Granger et al., 1961, p. 1199.

## ORE DEPOSITS

A generally accepted descriptive terminology concerning the structural configuration of the deposits in the area has evolved. Ore is generally termed *trend* ore if the form of the deposit is tabular, with the long dimensions nearly parallel to the bedding, or *stack ore* if the deposit has a sizeable vertical extent. Granger et al. (1961, p. 1188-1189) have proposed another classification of the deposits, adopting the terms *prefault* and *postfault* and using subclasses based at least in part upon color of the ore. Trend ore appears to be more or less equivalent to the prefault ore and stack ore to postfault ore. It is not entirely clear that trend ore is actually "prefault," as the apparent displacement of black, ore-bearing zones would suggest. It is possible that the organic matter, shown by the writer and others to be similar to material produced in the early stages of coal formation, was introduced into the host rock before faulting (at least the dip-slip faulting) and that there then followed introduction of low-valent uranium and vanadium minerals. It therefore appears preferable to discuss the mineral associations based upon relative valence of uranium and/or vanadium and physical character of the occurrence, a scheme which did not appear meaningful until completion of mineral identification.

## LOW-VALENT ASSOCIATIONS

Those minerals containing low-valent uranium and/or vanadium which are disseminated within sandstone occur in both the trend and stack ores.

Attempts by the writer to identify the minerals present in the trend ore have been only partly successful. The only uranium and/or vanadium mineral identified is coffinite, U(SiO4)1-x(OH)4x. The submicroscopic texture of this mineral is indicated by line broadening on X-ray powder patterns and also by the fact that the mineral is not observed in thin-section. Coffinite grains are probably less than .0001 mm in diameter. Vanadium has been shown to be present by spectrographic analysis; however, attempts to identify the form in which vanadium occurs in the trend ore have been fruitless.

Minerals containing low-valent uranium and /or vanadium which occur in the stack ore bodies include grains of uraninite, $UO_2$ (identified by the writer), coffinite as grains (tentatively reported in the district by Granger et al. (1959, p. 27, and 1961, p. 1198), and as thin coatings on sand grains (reported in the district by Granger et al. (1961, p. 1189, 1198), and montroseite,[2] VO(OH) (reported by the writer).

Uraninite occurs in minor quantities as replacement of sand grains, as well as fracture fillings. Actual replacement of grains is shown by a feldspar grain which had been transected, leaving two adjacent splinters with identical optic orientation. Associated with the replacement is a fracture coating of pitchblende.

Some fracture planes in the area of stack ore bodies are coated with montroseite.

## INTERMEDIATE VALENT ASSOCIATIONS

Paramontroseite, VO2, appears to be a common constituent of the stack ore, occurring much the same as montroseite, that is, both as disseminated grains and as fracture plane coatings. Occasionally the two minerals are found together.

1 University of Michigan Ph.D. thesis. The geology and mineralogy of Section 22 mine, Ambrosia Lake uranium district, New Mexico.

[2] Some confusion exists in the literature concerning the D-spacings for montroseite and paramontroseite. The writer is indebted to Miss A. D. Weeks, of the U.S. Geological Survey, for unpublished data on the powder pattern of montroseite (written communication, 1962)

Doloresite, $V_3O_4(OH)_6$, a mineral not previously reported from the district, has been identified on fracture planes in areas of stack ore.

In dark blue sandstone adjacent to one of the doloresite-bearing fracture surfaces, the color appears to be imparted by disseminated "corvusite." Corvusite has been reported from the district by Knox and Gruner (1957, p. 19) but is an incompletely described mineral which may actually be " . . . an intimate mixture of two or more closely related phases" (Evans and Garrels, 1958, p. 144). The evidence for the tentative identification of corvusite includes the color of the rock, the spatial relations of identifiable minerals (doloresite adjacent to and pascoite, $Ca_3V_{10}O_{28}.16H_2O$, as encrustations upon the dark blue sandstone), and the previous identifications of the mineral by others.

## HIGH-VALENT ASSOCIATIONS

Tyuyamunite, $Ca(UO_2)_2V_2O_8.5\text{-}8 1/2H_2O$, has been identified as disseminations within sandstone and also as fracture coatings in areas within and adjacent to stack ore. Metatyuyamunite, $Ca(UO_2)_2V_2O_8.3\text{-}5H_2O$ (identified by this writer) and carnotite, $K_2(UO_2)_2V_2O_8.3H_2O$ (reported by Granger et al., 1961, p. 1199), occur on fractures.

High-valent minerals encrusting mine workings include pascoite, bayleyite, $Mg_2(UO_2)(CO_3)_3.18H_2O$, a mineral not previously reported from the district, and andersonite, $Na_2Ca(UO_2)(CO_3)_3\ 6H_20$.

## DISCUSSION OF THE ASSOCIATIONS

During the field studies, the writer recognized a tendency for the mineral associations to occur in a crudely zoned fashion; however, it was not until identification had been completed that the remarkable zoning of minerals by valency within the deposits became evident.

Fringing each of the three stacked ore bodies which were being mined at the time of the field studies was a sequence of minerals, nowhere complete, and sometimes "telescoped," which was always rudely arranged outward in order of increasing valency. This tendency was further suggested by the spatial relations of pyrite and marcasite and goethite and hematite. Particularly well-developed were the sequences of vanadium-bearing minerals. When a composite sequence was compiled, it essentially duplicated the "acid suite" of vanadium minerals proposed by Evans and Garrels (p. 131-149). This appears to be the first reported duplication in nature of the complete "acid suite."

The discussion by Evans and Carrels (p. 131-149) concerning the development of the "acid suite" through alteration seems completely applicable to the associations at Section 22 mine. Montroseite appears to be the "primary" low-valent vanadium mineral, the alteration of which gives rise to the other members of the suite. Montroseite may alter rapidly to paramontroseite, a metastable species, by a solid-state oxidation, probably under weakly reducing conditions. Doloresite forms from either montroseite or paramontroseite by a solid-state alteration under weakly oxidizing and acid conditions. Doloresite is the mineral which first indicates the "acid suite" sequence. "Corvusite" is believed to form by acid waters leaching ore and moving the vanadium into adjacent sandstone. Carnotite and the calcium analogs, tyuyamunite and metatyuyamunite, are believed to have stability with respect to corvusite under conditions of higher oxidation potential or pH or both. Pascoite (occurring as an encrustation) is a special case, occurring where water is evaporating into the mine atmosphere.

The present distribution of minerals indicates that the primary ore deposits were of low valence and that alteration by oxidizing processes has imposed the intermediate and high-valent suites of minerals upon the low-valent association. The length in time of this alteration is not known. Whether the altering fluids were acid originally or were modified locally as alteration progressed is likewise unknown.

The Eh and pH of waters issuing from drill holes within the mine were measured (Corbett, 1961). Although considerable difficulties attend such measurements, they appear to be sufficiently reliable to indicate that even in (the then) newly opened areas of low-valent mineral associations, the waters have an oxidation potential in which only the high-valent minerals are stable. This observation, combined with information concerning the chemical character of the mine waters and the fact that pascoite, bayleyite, and andersonite are presently forming where conditions are favorable, strongly indicates that the leaching of uranium and vanadium by oxidizing and slightly alkaline ground water is continuing at present.

The writer gratefully acknowledges the support of Kermac Nuclear Fuels Corporation during his field studies in the summers of 1959 and 196o. The writer is indebted to the University of Michigan for use of research equipment and to the faculty of the Department of Geology and Mineralogy for suggestions and encouragement during this study.

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# *Geology and Ore Deposits of the Southeastern Part of the Ambrosia Lake Area*

GEORGE W. HAZLETT AND JUSTIN KREEK

## INTRODUCTION

This is the introductory paper to the three following detailed papers on the geology and the uranium ore deposits of the Ann Lee, Sandstone, and Cliffside mines.

This paper describes the general geology of the ore trends in sections 25, 26, 27, 28, 33, 34, 35, and 36, all in T. 14 N., R. 9 W., McKinley County, New Mexico. All except one of these sections (section 25) contain known uranium ore bodies. This group of sections is herein entitled the southeastern part of the Ambrosia Lake area of the Grants district (fig. 1).

## HISTORY

Ore was discovered by surface drilling in the southeastern part of the Ambrosia area early in 1956 by C. N. Holmes, Director, Strategic Minerals Section of Phillips Petroleum Company. The initial discoveries were made in sections 28 and 34. Subsequent drilling during 1957 and 1958 showed that the ore deposits occurred in separate trends extending east and west from these sections. The ore deposits were delineated by surface drilling with rotary type shot-hole rigs. Drilling depths ranged from 500 to 800 feet. Resistivity and gamma logs were made of all the holes, and self-potential logs and directional drift surveys were made of most of the holes.

The first development in the southeastern Ambrosia Lake area was the excavation of the Ann Lee shaft in section 28. This shaft was started in 1957 and was completed to a depth of 740 feet in early 1958. Ore production began in June 1958.

The Sandstone shaft in section 34 and the Cliffside shaft in section 36 were both started in 1958. The Sandstone shaft was completed in June 1959 at a depth of 970 feet, and ore production began in September 1959. The Cliffside shaft was completed in February 196o at a depth of 1497 feet, and ore production began in October 196o.

## STRATIGRAPHY

The rocks penetrated by exploration and development drilling range in age from Jurassic to Upper Cretaceous. Two holes were drilled into older rocks and data from these holes were incorporated into a generalized columnar section (fig. 2). Stratigraphically, this paper is limited to the Morrison Formation.

### MORRISON FORMATION

The Morrison Formation conformably overlies the Jurassic Bluff Sandstone and is truncated by the Cretaceous Dakota Formation. In the southeastern Ambrosia Lake area, the Morrison Formation ranges from 400 to 500 feet in thickness and is divided into three lithologically distinct members, the Recapture Member, the Westwater Canyon Member, and the Brushy Basin Member, in ascending order.

#### Recapture Member

The Recapture Member is comprised of a series of red, green, or mottled bentonitic mudstones and siltstones interbedded with red and gray, fine-grained, silty sandstones. The member ranges from i oo to 130 feet in thickness. The upper part contains local lenses of sandstone lithologically similar to the overlying Westwater Canyon Member, which represents an intertonguing of the two members. In many places, the contact between the two members is indefinable.

There are no known uranium ore deposits in the Recapture Member in this area.

#### Westwater Canyon Member

The Westwater Canyon Member ranges from 150 to 225 feet in thickness. The member is mainly composed of feldspathic to arkosic fluvial sediments ranging from siltstone to conglomerate with interbedded bentonitic mudstone. The member varies in color from red or tan to gray or white. The mudstones are red, gray, green, or mottled.

The sandstone beds are cross-stratified and contain abundant cut-and-fill structures made by complex channel systems. Crude graded bedding is visible in the coarse-grained units; the fine-grained units tend to be thin-bedded to massive. Sorting and rounding are variable and range from poorly sorted, subangular grains in the coarse units to well-sorted, sub-rounded grains in the fine-grained units. Combinations of these textures are common within individual beds. The fine-grained units tend to persist over longer distances than the coarse-grained units.

Mudstone beds occur in all horizons within the Westwater Canyon Member and range from a few inches to 4o feet in thickness. The thick beds persist over several thousands of feet and the thin beds often intergrade with sandstone units or may be scoured out within a few feet. Mudstone pebble conglomerates are common and represent reworked or remnant mudstone beds. Siltstones and marlstones have been observed underground but are rare.

Vertical gradation from sandstone to mudstone is extremely rare. The mudstone beds directly overlie sandstone beds which contain both fine- and coarse-grained units, with no intervening transition zone. A few examples of channels and scours filled with mudstone have been seen. There are places where the upper contact of the mudstone appears to be gradational, but laterally it becomes an erosional contact. With few exceptions, the lateral limits of the mudstone units are determined by scours filled with coarse-grained sandstone.

Correlation studies using self-potential and resistivity logs of surface drill holes indicate that four major mudstone beds

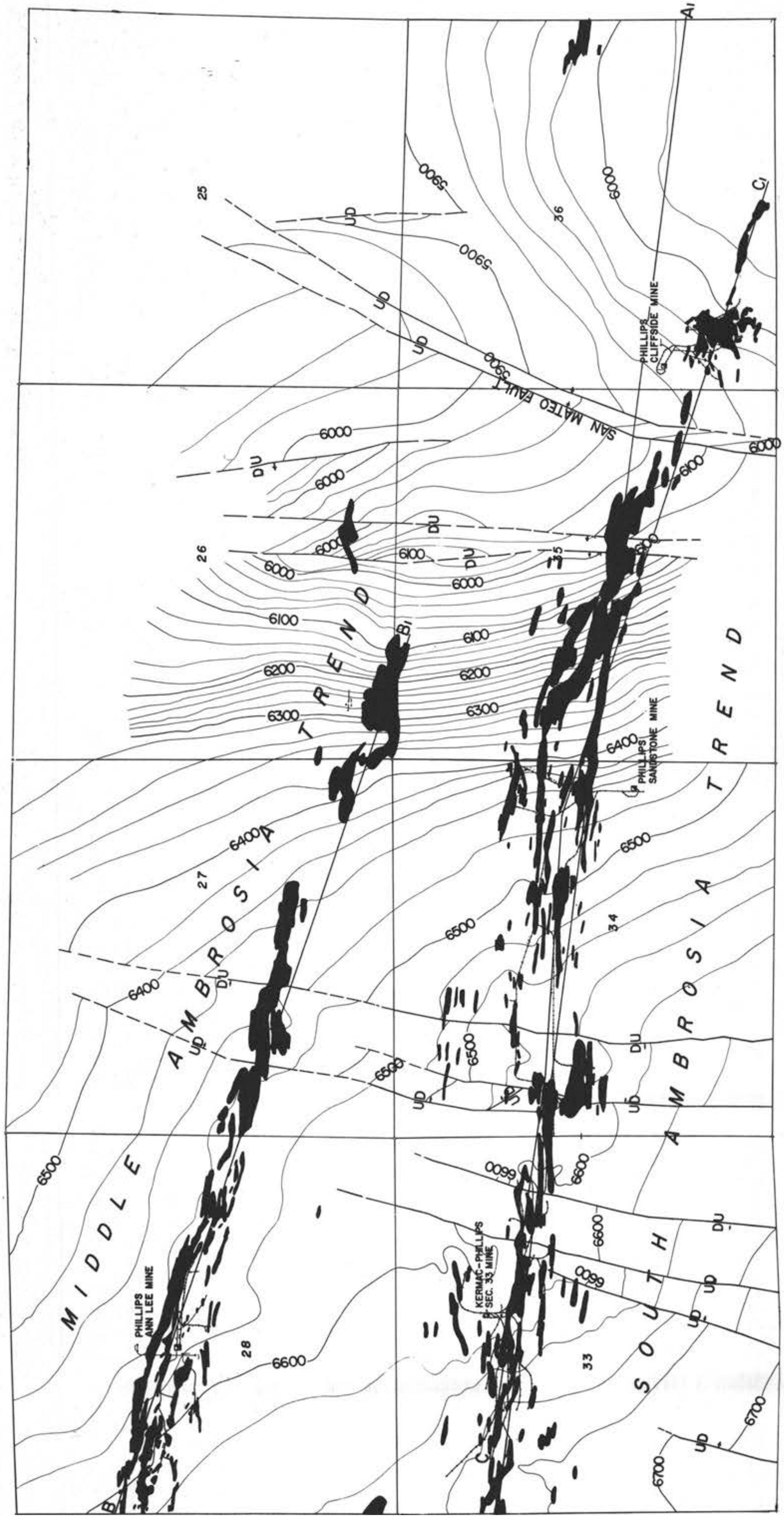



Figure 1

ORE DISTRIBUTION AND STRUCTURE CONTOUR MAP OF THE SOUTHEASTERN AMBROSIA LAKE AREA

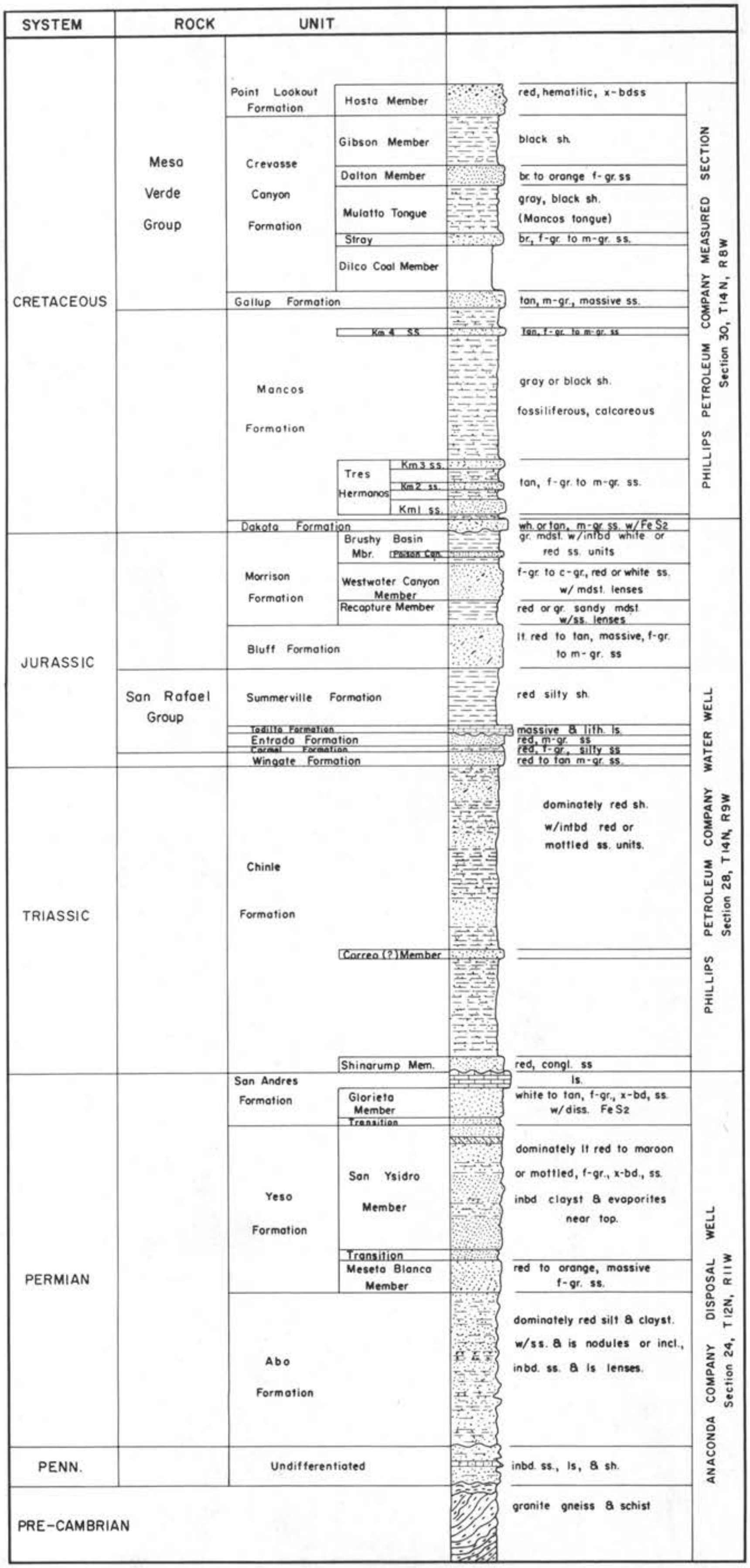



Figure 2

COMPOSITE COLUMNAR SECTION SOUTHEASTERN AMBROSIA LAKE AREA

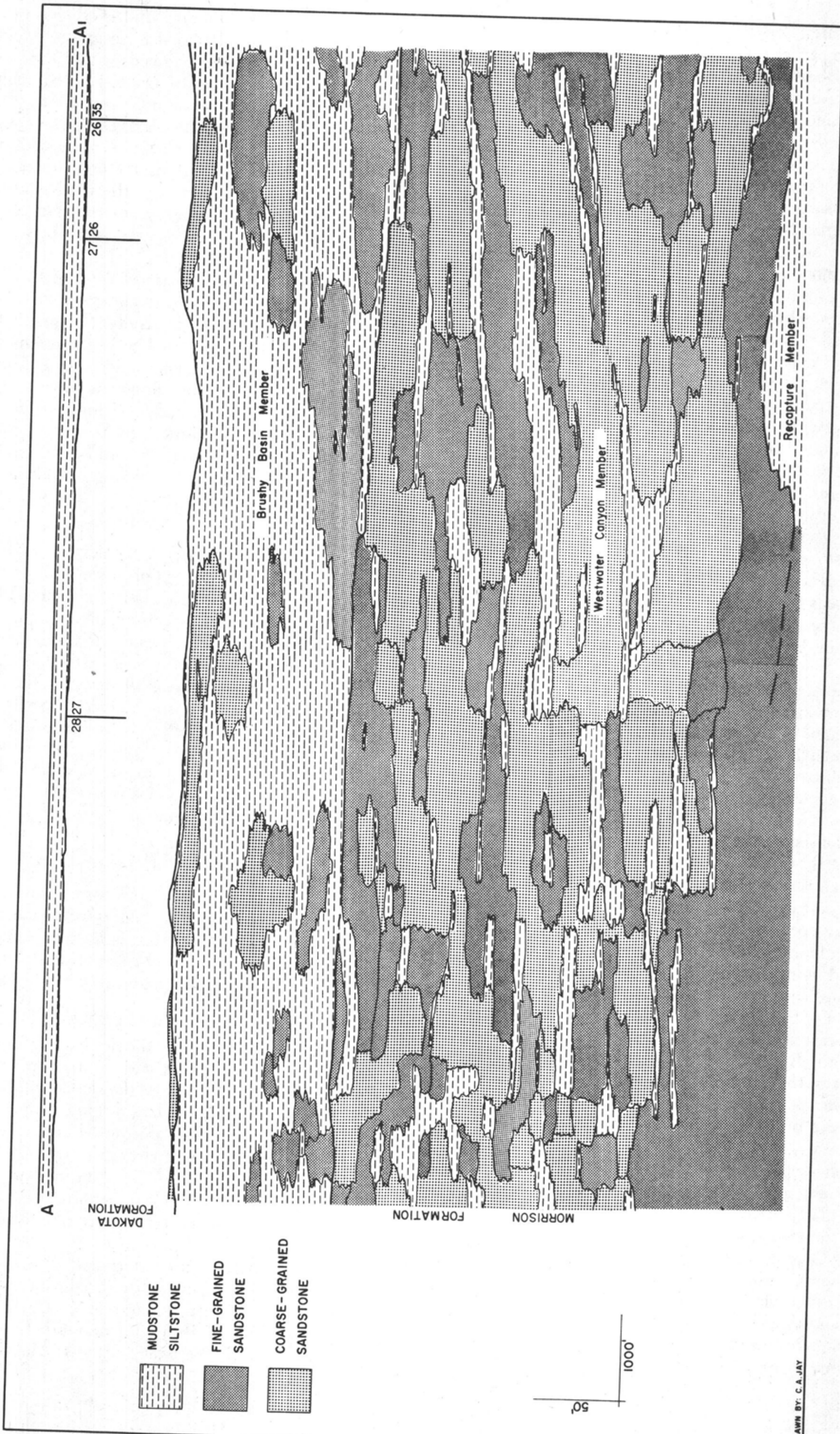



Figure 3

LITHOLOGIC LONG SECTION OF MIDDLE TREND LOOKING N. 20 E.

within the Westwater Canyon Member persist over enough of the southeastern part of the Ambrosia Lake area to be used to correlate and subdivide the member. On this basis, the sandstone units have been designated (in ascending order) The A, B, B1, C, and D zones. The long sections (fig. 3, 4) show that the mudstone beds are discontinuous, but that other or equivalent beds of similar stratigraphic position make it possible to carry a practical correlation.

*A Zone.* The basal 4o to 8o feet of sandstone of the Westwater Canyon Member is designated the A zone. The sandstones of this zone are, generally, finer-grained, thin-bedded to massive, and more poorly cemented than those of the overlying zones. Erosion surfaces and intraformational disconformities are common and tend to persist over longer distances as compared with the overlying zones. Discontinuous mudstone lenses or mudstone cobble units are common. The ore bodies within the A zone are elongate in the direction of deposition of the coarse-grained sandstone units and are frequently associated with a disconformity or a contact between coarse- and fine-grained units.

The mudstone separating the A from the B zone ranges in thickness from a few inches to 25 feet. The upper and lower contacts of the mudstone are irregular. The unit fills channels in the underlying A sandstone and intertongues with the overlying B sandstone.

B *Zone.* The B sandstone ranges from 3o to 5o feet in thickness. The beds in this zone contain more coarse-grained material than those of the A zone. The unit is thin-bedded to massive, contains fewer mudstone lenses, and is less friable than the A zone.

The mudstone separating the B zone from the $B_1$ zone ranges from a few inches to 15 feet in thickness. The bed is extremely lenticular and discontinuous and is the least distinct marker bed within the Westwater Canyon Member. Because of the discontinuity of this unit, it is difficult to distinguish the B zone from the $B_1$ zone in the electric logs. A discontinuous calcareous unit at the base of the $B_1$ zone serves as an aid for separating the two zones.

$B_1$ *Zone.* The $B_1$ sandstone is a transitional unit between the B and C sandstone beds. The $B_1$ sandstone ranges in thickness from 10 to 30 feet. Locally, the unit intertongues with the bed above or the bed below. The $B_1$ sandstone grades into siltstones and mudstones in the western half of section 34. A coarse-grained sandstone in section 33 seems to correlate to the $B_1$ zone. The coarse-grained unit grades into fine-grained rocks as the unit is traced west into section 32. In one small area along the east section line of 34, the C sandstones are channeled into the $B_1$ zone, but the $B_1$ sandstone is recognizable along most of the mineral trend as it is traced eastward.

Generally, the $B_1$ sandstone contains fine-grained, thin-bedded to massive units similar to the B sandstone. In some places its lithology resembles that of the C zone.

The mudstone separating the $B_1$ zone from the C zone ranges from a few inches to 20 feet in thickness. The bed forms an irregular contact with the beds above and below and is locally absent because of erosion.

C *Zone.* The C sandstone ranges in thickness from 15 to 6o feet. This bed contains the greatest variety of sediments and sedimentary features within the Westwater Canyon Member. Claystones, mudstones, marlstones, siltstones, gritstones, pebble conglomerates, angular mudstone slump blocks, mud-stone boulders in a variety of sizes, and mudstone flow structures have been observed underground. Cobbles of silty sandstone, lithologically similar to the Recapture Member, have also been noted. The sandstone beds within the C zone contain the highest percentage of coarse-grained material compared to the rest of the Westwater Canyon units.

The mudstone bed separating the C and D zones is the most persistent and widespread of the mudstone beds within the Westwater Canyon Member. The unit ranges in thickness from a few inches to 4o feet. Locally, the mudstone inter-tongues with the overlying D zone sandstone, but the bed is recognizable over most of the southeastern part of the Ambrosia Lake area.

D *Zone.* The D zone, the uppermost zone of the Westwater Canyon Member, ranges in thickness from five feet to 4o feet. The D sandstone is, generally, fine-grained and tends to be thin-bedded to massive. The bed contains abundant coarse material along the western side of the Ann Lee ore body but abruptly grades into fine-grained rocks to the south and east. Locally, the D sandstone intertongues with the overlying Brushy Basin Member. The D zone is generally recognizable over most of the southeastern part of the Ambrosia Lake area but appears to be missing in places in the southwestern portion of section 36.

### Brushy Basin Member

The Brushy Basin Member ranges in thickness from 90 to 15o feet. The member is comprised of green and gray mudstones, and red, gray, or green lenticular sandstones. The red and gray sandstones are lithologically similar to the Westwater Canyon sandstones. The green sandstones are not feldspathic and owe their color to a green, clayey, cementing material. The green sandstones generally occur in the middle and upper part of the Brushy Basin Member. Locally, a red or gray Westwater Canyon-type sandstone occurs near the base of the Brushy Basin Member and is interpreted as a tongue or lens of the Westwater Canyon Member. The bed probably correlates with the Poison Canyon tongue described by Rapaport (elsewhere in this memoir).

## STRUCTURE

The Grants district lies on the northeastern flank of the Zuni uplift. The regional dip of the beds is two to five degrees northeasterly. The regional structure is a broad homocline, dipping gently northeast into the San Juan Basin. Locally, the homocline is modified by Tertiary folds and faults.

### PRE-DAKOTA STRUCTURES

Others who have worked in the district have inferred that the Jurassic and older sediments were warped prior to deposition of the Dakota Formation. Evidence cited in the literature indicates that the beds were warped in broad north-trending and east-trending folds during Morrison time and before Dakota deposition. These structures were then complicated by subsidence of the San Juan Basin. Some of the evidence cited is based on the thickening and thinning of the Brushy Basin Member, which may or may not be a reliable datum reference.

Subsurface data from the southeastern part of the Ambrosia Lake area support at least part of the pre-Dakota structure hypothesis. Along the western side of section z8, the Brushy Basin Member appears to thin over a northerly-trending anticlinal structure in the Westwater Canyon Member. The

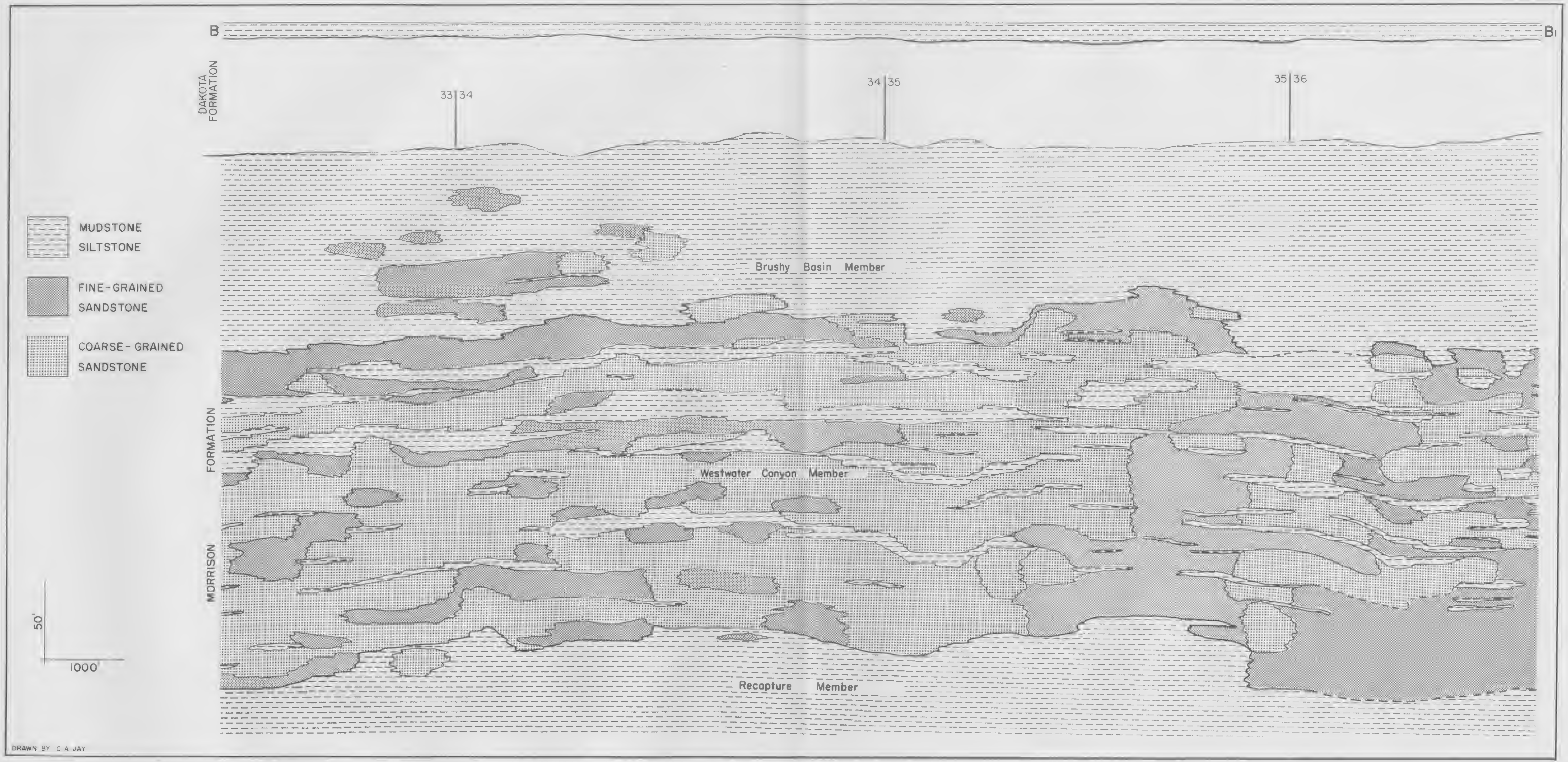



Figure 4

Lithologic long section of Southern Trend looking N. 20 E.

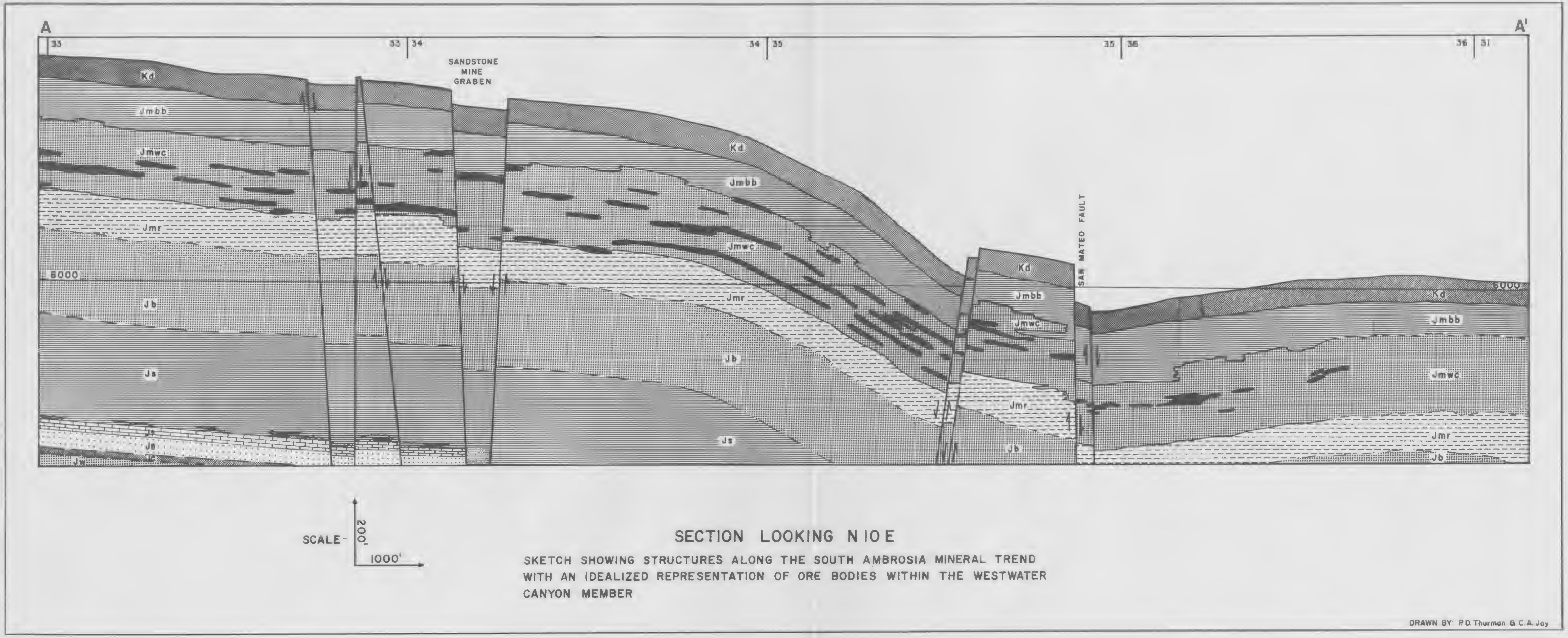



Figure 5

Structural long section of South Trend

structure is not reflected in the Dakota Formation. This anticlinal feature may have been caused by differential compaction.

The Cliffside mine workings intersect two small downthrown blocks bounded by arcuate faults. Surface drill holes which penetrated these blocks show no displacement of the Dakota Formation. The blocks are interpreted as pre-Dakota sedimentary pipes by Havenstrite *(Clark and Havenstrite,* this memoir).

### POST-DAKOTA STRUCTURES

The attached structure contour map and long section (figs. 1, 5) show that the dip of the beds along the southeastern part of the Ambrosia Lake area diverge from the regional dip and that the beds have been folded along the San Mateo fault sag. The San Mateo fault is interpreted as the eastern boundary of a horst which occupies the northeast-trending trough of a Tertiary asymmetrical collapse structure. The beds on the western limb of the syncline dip ten to fourteen degrees to the east and the beds on the eastern limb dip two to three degrees **to the northwest. It is postulated that the beds conformed to the regional dip of the homocline prior to the movement along the San Mateo fault sag. Collapse along the fault area caused the beds to slump into** the sag. The grabens which pass through sections 33 and 34 **are probably** tension relief features caused by the eastward movement of the beds. One set of joints, in the major system common to the area, parallels the collapse structure.

## URANIUM DEPOSITS

### ORE TRENDS

Three subparallel, northwest-southeast-striking ore trends are recognized in the Ambrosia Lake area. These trends have been labeled the North trend (Rio de Oro area), the Middle trend (Ann Lee area), and the South trend (Sandstone—Cliffside area). Only the Middle and South Ambrosia Lake trends (fig. 1) are covered in this paper.

In the southeastern end of the Ambrosia Lake area, the Middle and South trends are about one mile apart. The trends converge in sec. 3o, T. 14 N., R. 9 W., but both extend farther west.

Primary ore deposition within the trends appears to be dependent on lithology and carbon content, with redistributed ore locally affected by both pre- and post-Dakota structures. Outside the ore trends, the Westwater Canyon sandstone units become finer-grained and more massive.

#### Middle Trend

The Middle trend can be traced from sec. 3o, T. 14 N., R. 9 W., to sec. 32, T. 14 N., R. 8 W., a distance of about seven miles. It ranges from 1000 to 1500 feet in width. The general strike of the trend is N. 7o W., but it ranges from west to N. 6o W.

All the ore bodies of the Middle trend occur in the upper Westwater Canyon Member, the $B_1$, C, and D zones. Some workers have interpreted the sandstone unit at the base of the Brushy Basin as the Poison Canyon tongue. This unit merges with the Westwater Canyon sandstone in the west half of section 28 and is included there as part of the D zone.

The ore bodies in the Middle trend tend to occur higher, stratigraphically, along the northern side of the trend and step down, stratigraphically, toward the southern side. For **example, a north to south cross-section of the ore trend in section z8 would show an ore body in the** D **zone on the north side, successively lower ore bodies in the upper and lower C zone, progressing to an ore body in the upper $B_1$ zone on the south** side. There also seems to be a progression from the upper Westwater units in **the western end of the trend toward lower units in the eastern end of the trend, although the lowest known ore body in the trend occurs in the B sandstone in section 35.**

**The ore bodies in the Middle trend are more continuous along trend and tend to be more consistent in grade than ore bodies in equivalent units of the South trend. So far as is known, there are no thick, low-grade ore bodies along this trend.**

#### South Trend

**The South trend can be traced from sec. 3o, T. 14 N., R.** 9 W., to **sec. 36 T. 14 N., R.** 9 **W., a distance of about five miles. The general strike of the trend varies from east-west to N. 6o W. Mineralized rock has been found farther east along the trend, but the easternmost known ore body is in section 36.**

**Ore bodies in the South trend have been found in every unit of the Westwater Member, but none has been found in sandstones of the Brushy Basin Member in the southeastern end of the trend. The width of the trend ranges from moo to 300o feet. The ore bodies tend to follow a general echelon** arrangement and occur, progressively, in stratigraphically lower units from north to south. The steplike pattern of occurrence is not so marked as that of the Middle trend, but the general similarity exists. **The individual** ore bodies of the South trend exhibit fewer steplike features than those of the Middle trend. The ore bodies of the South trend have better grade at the west and east ends of the trend than the ore bodies along the middle portion of the trend.

Major faults of the area transect the ore trends at right angles. There seems to be a tendency for the ore trends to widen in the vicinity of fracture swarms and fault zones, although there appears to be a constriction of the ore trends near the San Mateo fault.

For a comparison of the distribution of ore by stratigraphic horizon in each trend, see Table 1.

## MINERALOGY

The ore bodies of the Middle and South trends contain the same associated minerals, although the relative proportions vary.

Coffinite has been identified as the uranium mineral in the black and brown sandstone ores in the district. The sandstone ores in the Phillips mines are essentially the same as the ores from the other sandstone mines and the contained uranium mineral is assumed to be coffinite.

Secondary uranium minerals are present in many of the older mine workings that are well drained. The most common of these is zippeite and tyuyamunite. The abundance of secondary minerals depends upon ventilation and drainage conditions within each mine. One small occurrence of yellow secondary uranium minerals of "premining" age was observed in the Cliffside mine workings *(Clark and Havenstrite,* this memoir). The mineral has not been identified, but the occurrence is noteworthy since the minerals were found moo

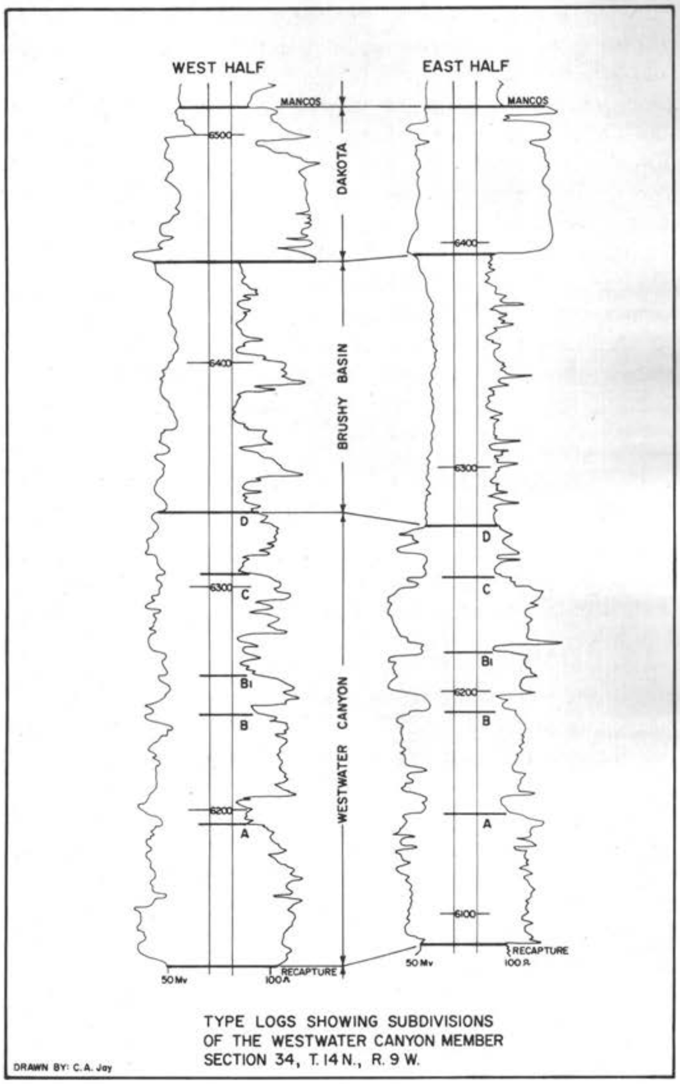



Figure 6

TYPE LOGS SHOWING SUBDIVISIONS OF THE WESTWATER CANYON MEMBER, SECTION 34, T. 14 N., R. 9 W.

TABLE 1

STRATIGRAPHIC DISTRIBUTION OF ORE WITHIN THE WESTWATER MEMBER BY RELATIVE PERCENT

| | A | B | $B_1$ | C | D |
|---|---|---|---|---|---|
| **MIDDLE TREND** | | | | | |
| *ZONE* | A | B | $B_1$ | C | D |
| Percent of total tons | 0 | 2 | 9 | 70 | 19 |
| Percent of total pounds | 0 | 2 | 7 | 75 | 16 |
| **SOUTH TREND** | | | | | |
| *ZONE* | A | B | $B_1$ | C | D |
| Percent of total tons | 23 | 28 | 21 | 20 | 8 |
| Percent of total pounds | 20 | 23 | 24 | 25 | 8 |
| **MIDDLE AND SOUTH TRENDS COMBINED** | | | | | |
| *ZONE* | A | B | $B_1$ | C | D |
| Percent of total tons | 16 | 19 | 17 | 37 | 11 |
| Percent of total pounds | 13 | 17 | 18 | 42 | 10 |

feet below the present water table. It occurs as clusters or "nests" around and between small groups of sand grains. The "nests" tend to be equidistant from each other. Austin (196o) suggested that the mineral was formed by the alteration of nearby feldspar grains. No radical differences in kaolin content have been noticed between the ore and the adjacent country rock in the Phillips mines.

Pyrite seems to be equally abundant in the Ann Lee and Sandstone mines but is sparse in the Cliffside mine. The largest crystals were found in the Ann Lee mine and were 1/4-inch cubes. The pyrite observed is believed to be authigenic.

Small, radioactive barite crystals, hematite, limonite, and thenardite (?) in minor amounts have been identified in the Phillips mines. No attempt has been made to determine their relative abundance.

Two general types of carbon are recognized throughout the district, ( 1) carbonaceous trash, coalified and carbonized wood and bones and (2) an unidentified form of carbon which impregnates the rocks, coating sand grains and filling fractures in such a way that many considered it to be a hydrocarbon residue and referred to it as "asphaltite" or "asphaltic material." This material is referred to as carbonaceous material and organic carbon in the papers on the southeastern Ambrosia Lake area.

An insufficient number of tests have been made on the carbonaceous matter to determine its composition, but an analysis of the material by the Research and Development Department of Phillips Petroleum Company indicates that it is nearly pure carbon.

The term *barren asphaltic material* has been used to describe uranium-deficient, black material which occurs in conjunction with the uranium ore bodies. The material was thought to be carbonaceous matter, void of uranium. Analyses of the several varieties of the material show that it contains varying quantities of vanadium, molybdenum, and manganese. Elmer Santos (written communication) points out that not only is the material uranium-deficient but it is low in carbon as well. In these papers, the material is called uranium-deficient, black material, or black barren material.

The black barren material is abundant in the ore horizons of the Ann Lee and Sandstone mines, but very little of this material is present in the Cliffside mine. It is thought that the black color is due to the presence of molybdenum, manganese, and vanadium.

The molybdenum mineral present in the uranium-deficient black material in and adjacent to ore bodies is jordisite, which alters to ilsemannite in dry mine workings. Samples from the Ann Lee mine contained up to o.36 percent molybdenum; samples from the Sandstone mine contained comparable amounts but samples from the Cliffside mine contained only half as much molybdenum.

The vanadium minerals present are presumed to be montroseite and paramontroseite. Pascoite occurs with secondary "postmining" minerals. Initial investigations have been made in the three mines to establish uranium-vanadium ratios. Incomplete results indicate that the ratio changes with the type and grade of uranium ore sample. Brown uranium ores contain uranium and vanadium in nearly equal amounts, but the vanadium values in black uranium ores increase at a slower rate as the uranium values increase. The ratios range from about 2:1 at 0.20 percent $U_3O_8$ to more than 6:I at 3.o percent $U_3O_8$.

Gray, metallic, foillike, native selenium has been found in the Ann Lee, Sandstone, and Cliffside mines, and gray, acicular, selenium crystals have been found in the Cliffside mine. In each of the mines, the selenium was found associated with mudstone inclusions within or adjacent to ore. Some of the mudstone inclusions contained a bright red material which is suspected to be the red variety of native selenium, but tests for identification were inconclusive. Selenium, if present in the sandstones, is masked by the ore. Ferroselite has been reported in other mines in the district but has not been identified in any of the Phillips mines.

Ores from the Cliffside mine contain the highest selenium values (0.029 percent average) of the three mines, and ore from the Sandstone mine contains the least.

Calcite is abundant throughout the Westwater Canyon Member as the principal cementing material, although the calcite content is notably higher within the ore bodies than in the adjacent waste rock. Calcite concretions and shells are found adjacent to the ore bodies. Frequently calcite is concentrated above permeability barriers such as mudstone units and scour surfaces. These calcareous concentrations occur in both ore and barren rock.

Kaolin is common in the sandstones throughout the Westwater Canyon Member.

# *Geology and Ore Deposits of the Ann Lee Mine, Ambrosia Lake Area*

JOHN B. SQUYRES

## INTRODUCTION

Section 28 of T. 14 N., R. 9 W. is the northwesterly section of those discussed by Hazlett and Kreek in this memoir. It lies for the most part within a broad, regional valley eroded in the Mancos Shale, though the northeastern corner of the section includes foreslopes of the higher Gallup Sandstone topography.

Commercial grade uranium was first discovered in section 28 by the Strategic Minerals Section of Phillips Petroleum Company early in 1956. Subsequently, nearly 30o exploration holes were drilled, to an average depth of about 75o feet. The existence of an ore body or group of ore bodies, of about one million tons was established, and sinking of the Ann Lee mine shaft was commenced in 1957. The shaft has two mining levels, a main level at a depth of 66o feet and a sublevel at 72o feet.

During development and mining of the ore body to date, more than 30o additional surface holes have been drilled. Drilling now completed forms a rough grid of holes spaced about 1000 feet apart over the whole section and a grid of holes on 50- to r oo-foot spacings within the area of ore occurrence. The Ann Lee mine remains the property of Phillips Petroleum Company,' but mining operations are currently being conducted under contract by K.S.N. Mining Company.

Possibly two thirds of the original ore reserves in the mine have been removed and half of the remaining known ore is extensively blocked out. The workings nearly span the section in an east-west direction, and at their widest point, expose part of the upper Westwater Canyon Sandstone Member for nearly r000 feet in a north-south direction.

## GENERAL GEOLOGY

### STRATIGRAPHA

#### Recapture Shale Member

Although a number of drill holes in section z8 have penetrated a short distance into the Recapture Shale Member, only one hole has been drilled completely through it. The self-potential log of this hole indicates that the Recapture Shale Member is 105 to 125 feet thick. Intertonguing of the Recapture Shale Member and the overlying Westwater Canyon Sandstone Member in section 28 is indicated by a transitional zone, as much as 75 feet thick, consisting of poorly sorted silty sandstone, interbedded with varying amounts of very coarse-grained sandstone. The coarse-grained sandstone resembles the Westwater sandstone in degree of sorting, rounding, and detrital mineral content. It generally is brick-red.

#### Westwater Canyon Sandstone Member

A typical section of the Westwater Canyon Sandstone1 Member of the Morrison Formation taken near the middle of section 28, where the contacts are fairly well defined, is shown in Figure 1. Persistent features across the section are the topmost, fine-grained sandstone (the D zone of Phillips Petroleum Company); the next thick sandstone unit, with a prominent coarse-fine contact in the middle part (the C zone); and the next two underlying mudstone beds. The two upper mud-stone beds are considered to be tongues of the overlying Brushy Basin Shale Member. The lowest of these tongues thickens to the north and west, and attains a thickness of 40 feet in the northwestern corner of the section. East and south of the mine shaft, it is very thin or absent.

Within the area opened by extensive mine workings, coarse-grained sandstone is somewhat more abundant than fine- or medium-grained sandstone. Development drifts in areas away from ore are more commonly in fine- to medium-grained thin-bedded sandstone, and surface drilling data also suggest that fine- to medium-grained sand is predominant away from the ore bodies. Rapid vertical and lateral changes in lithology are common throughout the section, however.

In the coarse-grained sandstone beds, basal and internal scour surfaces are common and are usually marked by mudstone-pebble conglomerate beds a few inches to one foot thick and several feet to several hundred feet in length. They generally end by truncation against a similar scour feature. Individual scour or channel fillings first appear as knife edges, pointed west, and thicken eastward at the expense of the bed below. Within a single "channel," the lithology is variable and is characterized by truncated beds, rapid lateral variation, and crudely graded bedding. Cross-bedding is very common. The finer-grained sand units are usually thin-bedded or massive or exhibit cross-bedding only on a very small scale. Silt-stone beds are comparatively rare and seldom attain a thickness greater than one or two feet or a length over a few tens of feet.

Mudstone beds occur at all horizons within the Westwater Canyon Sandstone Member and range from one or two inches to 3o feet in thickness. They may pinch out laterally in a few feet or persist over a large part of the section. The upper and lower surfaces of mudstone beds may be conformable with the adjacent beds or they may be erosional surfaces. Commonly, both gradational and erosional features will alternate on the same surface. Thin mudstone beds intersected by a scour surface often pass laterally into mudstone-pebble conglomerates.

Plant remains are neither rare nor especially abundant in the portion of the Westwater Canyon Sandstone Member exposed in the Ann Lee mine workings. Individual logs and fragments of branches are occasionally uncovered, and a few "trash piles" have been found, always in or very near ore. The smaller chips and branches are generally carbonized and highly uraniferous, whereas the logs are silicified, with a thin outer layer of carbonized material sometimes present.

Except for a few red sandstone lenses or tongues of doubt-

. The Phillips mines have been purchased recently by United Nuclear Fuels Corp.—V. C. K.

ful classification at the top of the Recapture Shale Member, all the Westwater Canyon sandstone in section 28 is light gray to white or, occasionally, light tan. The mudstone is generally pale green. Occasional clasts or thin beds of mudstone are of a paler color than usual. The paler color appears to be the result of bleaching. During the life of the mine, perhaps a half dozen brick-red mudstone cobbles have been observed.

### Brushy Basin Shale Member

The Brushy Basin Shale Member in section 28 consists of an upper unit 8o to loo feet thick and a lower tongue up to 3o feet thick, separated by a 3o- to 50-foot bed of Westwater Canyon sandstone. Where it is exposed in the mine workings by caved ground, the Brushy Basin Shale Member is a uniform pale green mudstone, with interbedded, fine-grained, silty sandstone lenses. Megascopically, the mudstone is usually platy but otherwise structureless and is remarkably free from organic remains of any sort.

## STRUCTURE

Aside from the regional dip of 2 to 3 degrees to the northeast, and possibly some broad pre-Dakota structures, there is no recognized folding or tilting of the beds in section 28. Significant faulting is likewise uncommon. Only two steeply dipping normal faults, having strikes of N. o° W. and N. 20° W., respectively, and offsets of about 18 inches, have been intersected in the workings. Fractures consisting of joints and faults with offsets of an inch or so are common; they occur singly or in groups or "swarms" of 2 to 5o or more, strike between N. 2o° E. and N. 20° W., and dip steeply in either direction. The swarms occur at irregular intervals and are often separated by hundreds of feet of undisturbed or sparsely fractured sediments. Individual fractures have regular, straight, or gently curving surfaces, and frequently branch or intersect other fractures. They rarely persist for more than 5o feet, and the average length is probably about 20 feet. Their vertical extent has not been observed, but it is probably

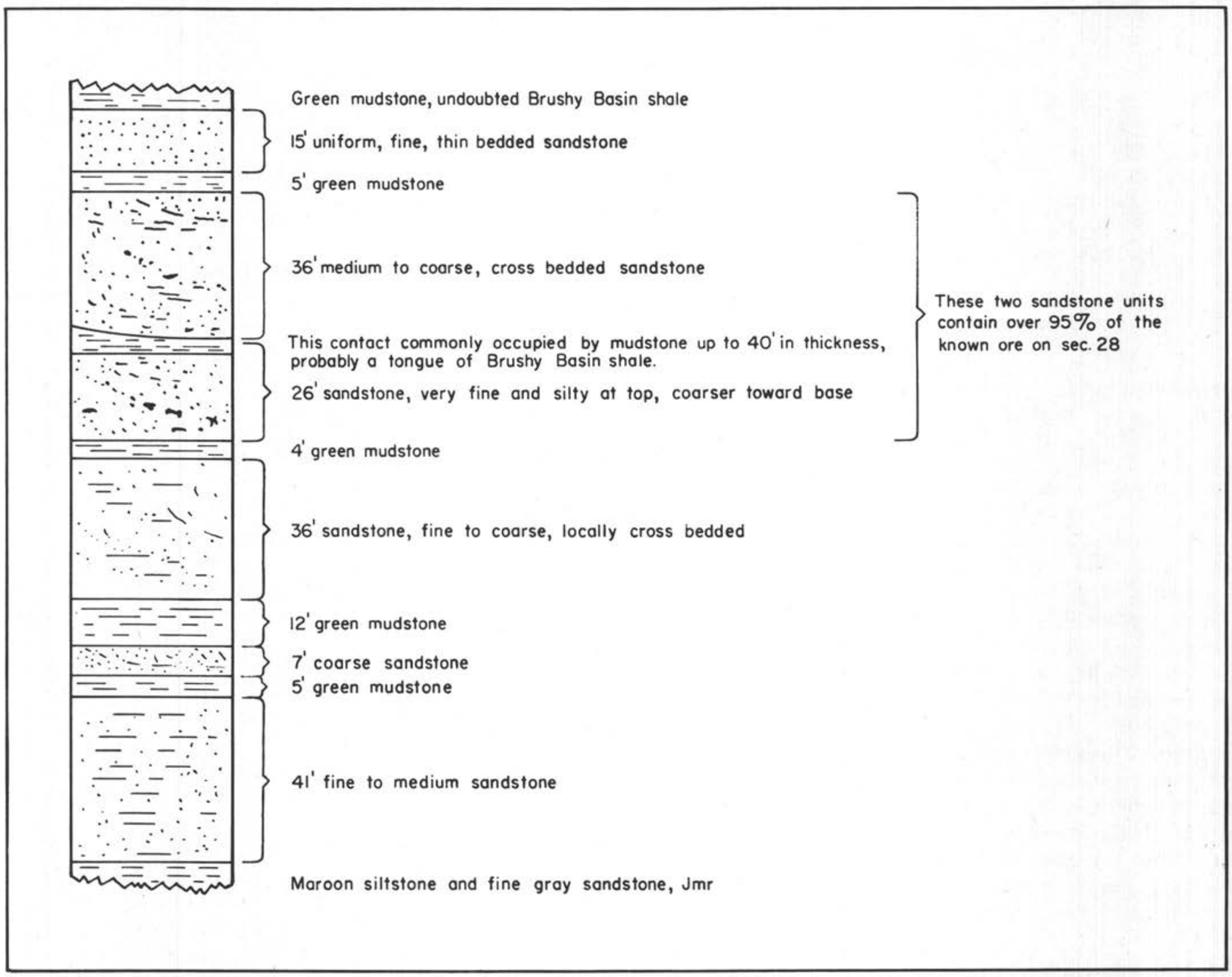



Figure 1

GENERALIZED COLUMNAR SECTION OF THE WESTWATER CANYON SANDSTONE FROM NEAR THE ANN LEE MINE SHAFT limited, since they end against mudstone beds and tend to be confined to specific lithologic units. Whether a given fracture swarm is repeated in lower or higher sandstone beds separated by more than a few feet of mudstone is not known.

One of the small faults mentioned previously has a vertical extent of at least 8o feet and transects two mudstone beds with an aggregate thickness of about 17 feet.

### SLUMP STRUCTURES

In the main ore body, and particularly in the western part of that ore body, evidence of gliding and slumping of various beds within the Westwater Canyon Sandstone Member is abundant. Mudstone layers and thick cobble conglomerate beds evidently underwent the most deformation and show the results most clearly.

In the mudstone-cobble conglomerates, flattening, elongation, and sometimes smearing out of the individual clasts has occurred, while layers of bedded mudstone are folded and contorted and frequently contain internal zones of shearing, shown by bands of lighter color adjacent to small folds, or sometimes containing broken, rounded, and rotated fragments strung out along the line of shearing in a manner reminiscent of boudinage structure. Adjacent to the deformed mudstone, the sandstone is often structureless, though a few feet away the same sandstone bed may exhibit strong bedding. It is the writer's opinion that deformation took place very shortly after deposition, while the sediments were still unconsolidated, waterlogged, and covered with only a few dozens of feet of overburden. The mudstone beds appear to have acted as lubricating planes upon which larger masses of sand were able to glide without much internal deformation. The effect is regarded as due to gravitational adjustment acting over short distances; for example, slumping at the banks of a local channel or possibly slippage in the direction of initial dip of the formation. Erosional surfaces truncating contorted beds have not been observed.

In the areas where deformation is most obvious, another type of structure is moderately abundant. This consists of a mass of more or less bleached mudstone, showing severe internal deformation and often containing admixed sand grains. The masses are elongated vertically and have either a dikelike form or the shape of a tadpole, tail down. Examples from one to seven feet in height have been observed. They cut across the bedding of the host sandstones and frequently show small offshoots or apophyses which invade the sandstone parallel to the bedding. Occasionally, faint upturning of the surrounding sandstone beds is noted, but more commonly the bedding becomes indistinct a foot or so away from the mudstone. These mudstone bodies are interpreted as small piercements. They cannot generally be related to a "source" bed below and probably originate in comparatively small masses of mudstone. The total vertical movement is probably only a few feet in most instances.

## ORE DEPOSIT

### FORM AND DISTRIBUTION

The Ann Lee ore deposit consists of one large pod, hereafter referred to as the main ore body, and 20 to 30 smaller, parallel, or satellite pods. The main ore body extends from the west section line to a point within 500 feet of the east section line, and originally contained more than half a million tons. It has a gross orientation of N. 70° W. and passes nearly through the center of the section. The small pods generally have a width to length ratio between 1: 5 and 1:20 and are closely parallel to the main ore body. They range in size from a few tons to about Ioo,000 tons and aggregate another half a million tons.

A few pods near the southern edge of the known ore-bearing zone appear to be oriented nearly east-west, but the majority of the small pods is oriented within a few degrees of N. 7o° W. With the exception of ore-grade material in a single drill hole in the southeastern corner of the section and an incompletely explored area in the extreme southwestern corner, all the known ore in section 28 is contained within a zone less than 1000 feet in maximum north-south width. This is the "middle trend" discussed in the general section of the introductory paper.

Another characteristic of the Ann Lee ore deposit, and particularly the main ore body, is continuity along trend. Bulges, embayments, or other irregularities in the shape of the ore body are apt to appear in successive cross sections for hundreds of feet, and die out or change shape gradually. One prominent roll or "step" is recognizable for nearly 1000 feet (fig. 2). Internal features, such as areas of higher grade or unusual texture, also tend to persist along trend.

It is noteworthy that, except for two areas of low-grade material in a fine-grained sandstone unit at the base of the Brushy Basin Shale Member, all the satellite ore pods are south of the main ore body. The northern boundary of the main ore body is quite sharp, and rarely has even weakly mineralized ground been discovered north of that boundary. On the other hand, ore pods and isolated mineralized horizons are abundant in the zone immediately south of the main ore body.

Along the west section line, the ore pods occupy a high stratigraphic position within the Westwater. All the ore is confined to a 4o- to 50-foot thickness of sandstone which is the topmost unit of the Westwater and is separated from the next sandstone bed by as much as 3o feet of mudstone and fine-grained sandstone.

Traced eastward across the section, the ore occupies a successively lower horizon within the Westwater Canyon Sandstone Member. This is partly because the host sandstone bed itself crosscuts downward at the expense of the underlying mudstone tongue until it rests against the next sandstone unit below. The ore also has a tendency to occupy a successively lower position within individual sandstone units. This is related to small, local cross beds, or "scours." The cross beds usually appear in section as a wedge pointing west and thickening to the east. Where the ore boundary extends across the truncated edge of one bed, it tends to assume the downward-sloping attitude of the superposed unit, and the net effect is a lowering of the stratigraphic position of the ore. The same phenomenon occurs in the smaller ore bodies immediately south of the main ore body, except that a very prominent contact between coarse-grained sandstone above, and fine- to medium-grained sandstone below appears to localize the ore, and it is the contact which is scoured to a lower position eastwardly.

All the ore bodies developed in section 28 to date show this eastward plunge to some extent, though irregularities are

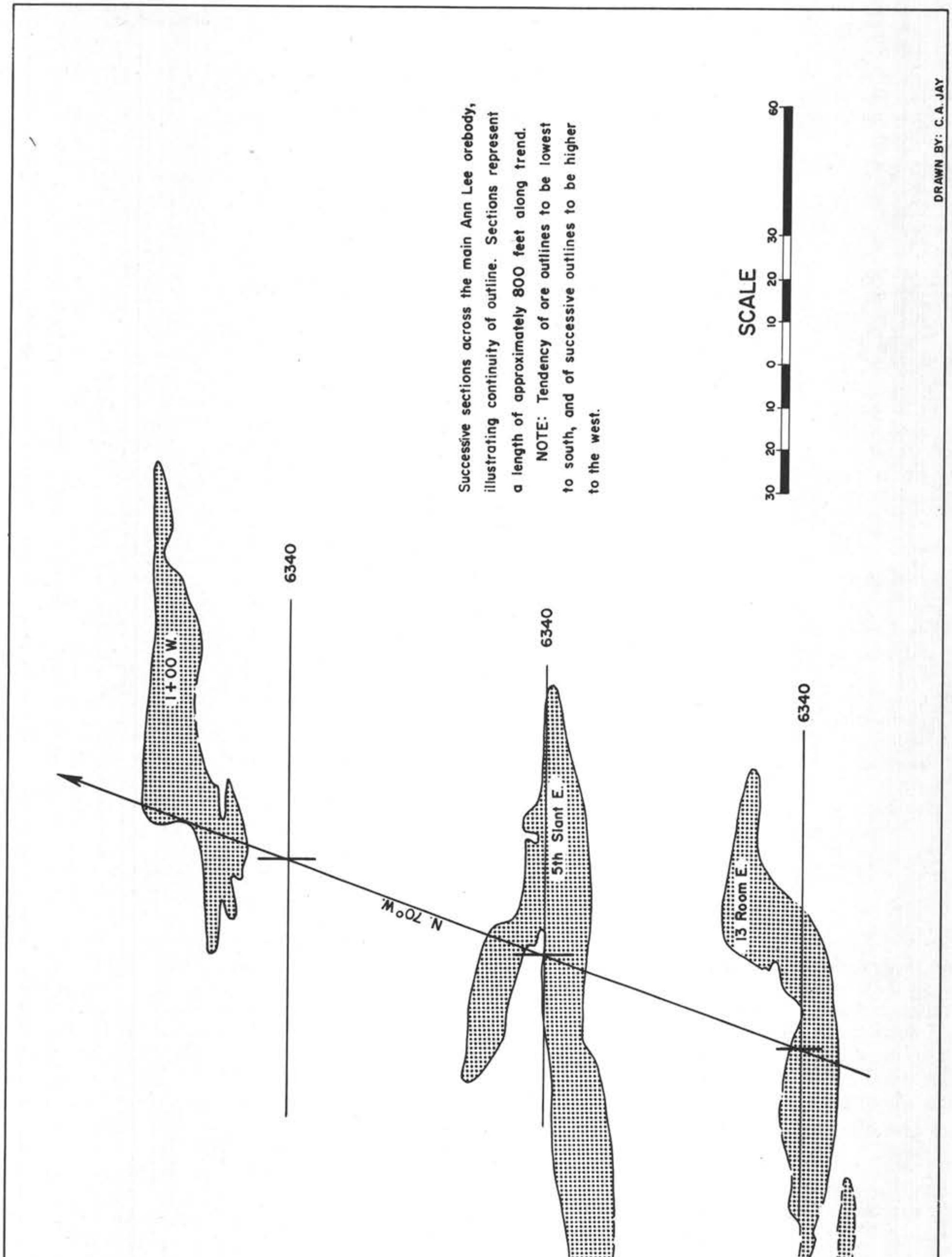



Figure 2

SUCCESSIVE SECTIONS ACROSS THE MAIN ANN LEE ORE BODY numerous. The average angle of plunge is about two degrees.

In addition to their eastward plunge, the Ann Lee ore pods show a pronounced "shingle" pattern; that is, successive ore pods tend to lie at deeper stratigraphic levels from north to south, and the southern part of a particular pod is often lower than the northern part. This, in spite of a 2- to 3-degree northwesterly dip of the enclosing beds. The pattern seems too widespread to be a coincidence, but the writer has no satisfactory explanation to offer.

All the known ore in section 28 is in the upper half of the Westwater Canyon Sandstone Member and more than 95 percent is in the upper one third. Except for a higher proportion of fine-grained sandstone, the lower beds appear to be inherently just as favorable for uranium occurrence as the actual ore-bearing beds.

As the mine workings were extended, a number of lithologic features were recognized which influence the distribution and character of the ore. Detailed knowledge of stratigraphy is limited to the area opened by the mine workings, but several lateral belts have been recognized within that area. They are particularly evident on the western side of the section, where the vertical extent of the ore is comparatively restricted. They are described here in order, from north to south (fig. 3).

### Belt I (Main Ore Body)

Belt I consists mostly of coarse-grained sandstone but is quite variable. Cross-bedding is very common. Finer-grained sandstone and occasional mudstone beds constitute the upper boundary of the ore. The lower boundary is generally a mudstone-pebble conglomerate, with coarse- or fine-grained material beneath. Slump structures are common, consisting of folded, "squeezed out," and distorted mudstone beds and mudstone "piercements." Occasionally, this zone has a well-defined boundary with a channellike cross section and a basal conglomerate. More often it grades into the adjacent zones by a gradual lateral decrease in degree of cross-bedding and lithologic variation. It is bounded on the north by fine-grained, more evenly bedded sandstone.

### Belt 2

Belt 2 consists of a coarse-grained, moderately cross-bedded upper unit overlying fine-grained, silty sandstone or siltstone with an erosional contact. This contact is the prominent contact with the upper sand unit shown in Figure 1. It extends into zone I but is beneath the ore horizon there and is probably deeply channeled over large areas. Resistivity logs of drill holes in the main ore body indicate that the lower unit is coarser-grained beneath zone 1 than in zone 2.

### Belt 3

Here the same coarse-fine contact is present, but the upper unit is very coarse-grained, and the contact is generally marked by a mudstone-cobble conglomerate or a thin bed of mudstone.

### Belt 4

Belt 4 consists of fine- to coarse-grained, predominantly thin-bedded or massive sandstone and contains discontinuous mudstone-cobble beds inclined in various directions and located at all horizons within the workings. Individual beds cannot be traced for more than a few tens of feet in any direction. This belt appears to be thick, lacking in distinctive strata, and without definite boundaries. Fine-grained sandstone beds are predominant in this belt, whereas they are subordinate in the other belts. Evidence of slumping is present but not widespread

### Belt 5

Belt 5 consists of thick, uniform, medium-grained sandstone containing few mudstone pebbles or cross-bedded units. A mudstone bed two to three feet thick is present, generally three to five feet below the base of the ore.

Within these belts, the character of the ore is influenced considerably by the host sediments. In the comparatively well-defined channel of belt 1, the ore is thick, uniform, continuous, and roughly lens-shaped in cross section. Where the coarse-fine contact is pronounced, the ore is also uniform and continuous, but it is more blanket-shaped, rarely being more than eight feet in thickness. The base of the ore is usually at the contact or a few feet above it. The ore only rarely "makes" into the underlying fine-grained unit, but where it does, it tends to be of exceptionally high grade.

Where the same contact is marked by a mudstone-pebble conglomerate or a mudstone bed, the ore is similar in appearance, but is thinner, irregular, and discontinuous.

In belt 4, the ore is very discontinuous and irregular, often ending abruptly, to occur again a dozen or so feet higher or lower in the section. It follows individual, thin, conglomerate beds, pinching out or invading the adjacent sandstone in random fashion. The ore also shows abrupt and unsystematic variations in grade. It occurs in a series of formless pods strung out in the N. 7o° W. direction, rather than as a single, elongated pod.

In belt 5, the ore body occupies a comparatively thick and uniform sequence of sandstone beds and is itself rather thick and uniform.

In summary, the Ann Lee ore bodies are associated with and controlled by filled channels, lithologic contacts, mudstone-pebble conglomerates, and thick sandstone units. They derive much of their gross form, orientation, and character from the character of their host sediments. Since the lithology of the sediments can generally be established from surface drill-hole information, the relationship constitutes a most useful tool in geologic interpretations and mine planning.

The control of ore outlines by lithology is most apparent on a comparatively large scale, as described above. An ore boundary at a specific point may cut smoothly across minor lithologic features and is likely to be related to lithology only in a general way (pl. 1-B).

In cross section, the ore bodies commonly have an elongated, irregular lens shape. The upper and lower boundaries tend to parallelism with the enclosing sediments, but the edges are most likely to cut sharply across lithologic features.

In at least two areas in the Ann Lee mine, an unusually wide, thick part of an ore body coincides with a fracture swarm. Similar occurrences are suspected elsewhere. In these localities, the ore usually has a dark, high-grade core surrounded by a wide, irregular "fading" halo. The darker core may be offset by the fractures, but the lighter material invades and fills the fractures or appears to have followed and moved outward from the fractures or to be dammed up by them.


Figure 3

Map of the west side Ann Lee ore deposit

Sometimes a single fracture offsets dark ore and "dams up" lighter material.

To the extent that the workings permit observation, the lighter, later, "fading" material is more common at the top of the ore bodies. It is also more common in the western half of the section, where the ore is stratigraphically and actually higher.

Fractures, individually and in swarms, which cut ore that does not exhibit the associated features of thickening, halos, and fading, are more common and more widespread than fractures which do show these features. Fracture control does not involve more than a few thousand tons at the most and is certainly a minor characteristic of the Ann Lee ore deposit.

## Character of the Ore

Uranium concentration in and adjacent to the ore bodies ranges from traces to more than seven percent $U_3O_8$. Material of higher grade than 1.50 percent is rare, however, and usually occurs in association with small "trash piles" of carbonized plant remains. The average grade of the ore is about 0.3o percent. Total production to date, including dilution, has averaged 0.24 percent.

In common with much of the rest of the Ambrosia Lake area, the ore material consists of a thin, tarry-appearing substance which impregnates the sandstone and coats individual sand grains. Tests of this substance by the research department of Phillips Petroleum Company indicate that the uranium carrier is, in its present state, almost pure carbon. The amount of carbon increases with uranium content, but whether the carbon-uranium ratio is fixed is not known. It is assumed that the specific uranium mineral present is coffinite, since the uranium mineral in similar ores in the district has been identified as coffinite.

The ore ranges in color from light brown through dark brown to black, with a subtle purplish cast apparent in the darker material. Color and grade of ore bear such a constant and close relationship that, with a little experience, grade of ore can be estimated consistently within a few hundredths of a percent in the 0.15 to o.6o percent range, and with considerably less accuracy, in the 0.02 to nearly I.00 percent range. Above about o.6o percent, the ore is black, and the estimate is probably based in part on a velvety appearance which is due to progressive obscuring of the grainy sand texture by coatings of ore material. It appears that the uranium-bearing material is brown and translucent in very thin films, and the color of the ore is proportional to the thickness of the coating. It is the writer's belief that the uranium content of the coating will be found to be constant, or nearly so, that the grade of a given portion of the ore body is determined by the amount of the coating material present, and that this in turn is a function of the thickness of the coating and the amount of surface coated. The finer-grained sandstone has a larger specific surface but possibly lower permeability and less available open space.

Commonly, the border of an ore body exhibits a fading-out of the ore grade compared to the more uniform interior. Usually, however, the ore grade is uniform to within an inch or less of the boundary, and even where fading is pronounced, there is generally a sharp visual boundary where the uranium content of the sandstone decreases five- or tenfold within a few inches (pl. 1-D).

There is no simple relation between thickness and grade. The thicker lens-shaped ore bodies tend to be higher grade in their thickest parts, but very high-grade ore is also common in blanketlike ore bodies only a few feet thick. Where adjacent coarse- and fine-grained beds are enclosed within the same body of ore, the finer-grained rock tends to contain higher-grade ore, but this relationship is by no means invariable. Mudstone cobbles within the ore may or may not be themselves mineralized. Clasts which are impregnated with uranium-bearing material generally exhibit some degree of distortion, such as elongation and flattening. The bleaching of mudstone cobbles is also related to degree of distortion. Clasts which retain their apparent original shape are generally of the same pale green color characteristic of thick, bedded mudstone layers. Possibly the original layered structure of the mudstone is relatively impermeable and resistant to penetration by altering fluids unless destroyed to some extent by mechanical deformation.

A very common feature of mineralized mudstone clasts is a narrow, apparently unaltered rim around a uniformly impregnated core. Less commonly, a zoned effect is produced by alternating rings of mineralized and barren mudstone (pl. 1-F).

## Minerals and Mineral Material Associated with the Ore

Two types of black, generally nonuraniferous, asphaltic-appearing material are associated with the ore. Both have been found only in close association with ore, and both occur, like the ore, as brown to black material impregnating the sandstone and coating the individual grains. They are distinct from the ore and from each other in many ways, however, and clearly constitute a separate chemical phase or phases. Originally, this material was called "carbonaceous residue" or "asphaltite," by analogy with the carbon-bearing ore material, but the few tests which have been made of it indicate almost no organic carbon. According to Elmer Santos (written communication), more extensive tests made by the U.S. Geological Survey yielded similar results. At present, the true composition of this material is not known to the writer. To avoid terminology problems, it will be referred to here simply as "barren material."

The most common of the two forms of barren material is about one tenth to one third as abundant as the ore and is usually black. Gray or brown patches have been found but are less common. The existence of material apparently identical to the black barren material in form and distribution but of a lighter shade, and occurring in two distinct colors (gray and brown), suggests that more than one substance is involved. Possibly the difference in color is due to a difference in oxidation state or to differential leaching of originally mixed materials. The color of a particular patch of this material is uniform, either all brown, all gray, or all black, with no evidence of fading at the edges. The barren material characteristically contains myriads of minute quartz overgrowths, the crystal faces of which impart to the rock a grainy, "sparkly" appearance lacking in the ore. These quartz overgrowths are common in the black barren material, less common in unimpregnated, bleached country rock, and relatively rare in the ore. There is a possibility that they do exist in the ore but have been obscured by the uranium-bearing material. Where quartz overgrowths are absent in the barren material, it has a

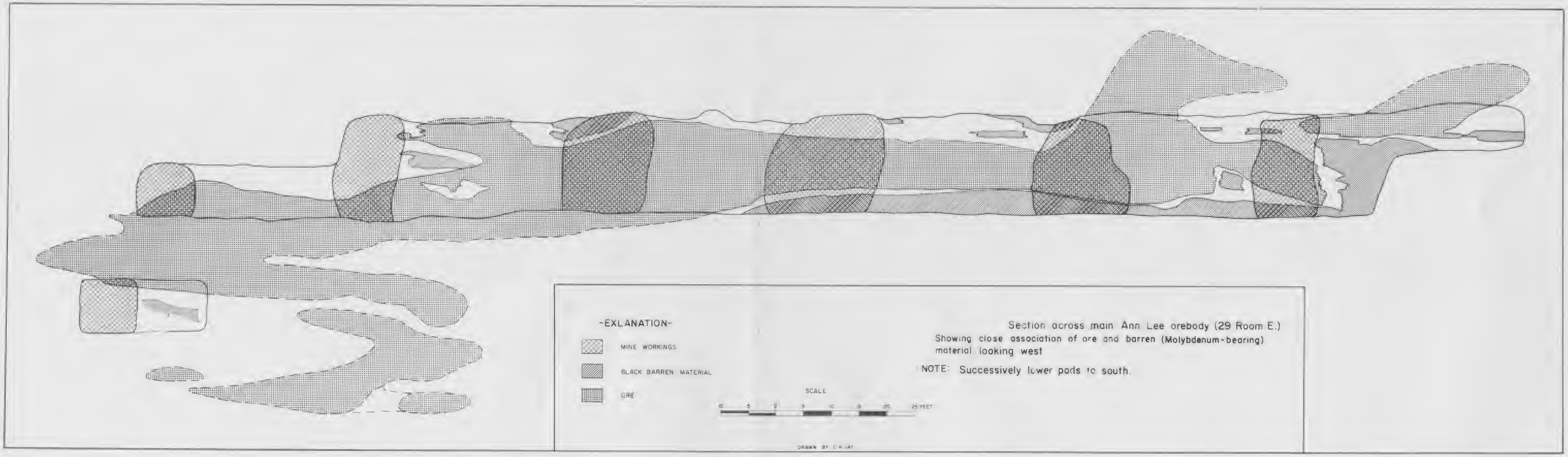



Figure 4

North-south across the main Ann Lee ore body dull, chalky luster, in contrast to the velvety or pitchy luster of the higher-grade ore. Whereas the ore exhibits fading near its edges, and has a fairly well-defined boundary surface which cuts across bedding features, apparently unaffected by minor variations in permeability and lithology, the barren material often selectively impregnates separate minute beds within a sand unit, apparently following little channels of higher permeability. The result is a fine lacework of lines in which each bed stands out as though inked. Some patches consist entirely of this wispy material, but more often the wispy pattern forms a fringe which, by thickening and merging of the individual filaments, grades into a solidly impregnated area. Often one or more sides of a patch of the denser barren material ends abruptly along an arcuate concave line which cuts across lithologic units in somewhat the same manner as the ore-bearing material. In each instance, the boundary is so sharp that a heavily coated sand grain may be in contact with an uncoated grain. This barren material is largely confined to the coarser-grained esandstone host rocks, and when it invades siltstone or very fine-grained sandstone, the wispy pattern is predominant. The material has a very definite and consistent spatial relationship to ore. Most often, the ore and barren material are separated by a few inches to a few feet of bleached, unimpregnated waste rock, but show a very marked tendency towards parallel contacts (pl. 1-D). This is true even of very sinuous or irregular boundaries. An embayment in the ore may be penetrated by a salient of the molybdenum-bearing material or occupied by a small patch of barren material. The relationship is not entirely reciprocal, however, since ore usually occupies a central position and barren material a peripheral position (fig. 4). The barren material also tends to reflect the character of adjacent ore, being thick where associated with thick ore, discontinuous when adjacent to discontinuous ore, and so on. It is very rarely found more than about 20 feet from the ore. It tends to be less continuous than the ore and often occurs in small patches or wisps at random intervals around the ore. A very few instances have been observed where the barren material is in actual contact with, or surrounded by, the ore. The ore in such instances is of low grade and exhibits fading borders.

The barren material will often acquire a coating of blue molybdenum oxide if exposed in the workings under conditions of moderate humidity for any length of time. Assays of the material have yielded results which vary from 0.10 to 0.36 percent Mo. Molybdenum is also present in the or material, but in much smaller amounts.

-Mudstone clasts impregnated or surrounded by the barren material occasionally show a curious feature: a border, a fraction of an inch to about two inches wide, of unimpregnated rock, surrounded by a ragged, irregular halo of the barren material. Mudstone clasts similarly impregnated or surrounded by ore material less commonly show a gap between the edge of the clast and the ore material.

A much less abundant type of black barren material also occurs in association with the ore. It is a dense, tarry appearing substance, which forms elongated lenses a few inches to one foot thick and one foot to ten feet long. The average length is about five feet. The lenses are usually at or near an ore boundary and may be outside the boundary, or just inside it. Lenses have also been found six feet or more within the ore, nearly in the middle of the ore body, however (pl. -E). They are more common when the ore boundary coincides with a lithologic boundary and are more common within fine-grained units than in coarser ones. They are always parallel or subparallel to adjacent lithologic boundaries and to the ore boundaries. Although conspicuous, they probably amount to about 1/ 10,000 or less of the volume of the ore. They characteristically have sharp, broadly curving boundaries and tapering ends and never show fading. Rarely, they exhibit a fritted or embayed pattern, similar in appearance to the pattern produced by wind erosion of a cliff. They do not contain the "sparkly" quartz overgrowths characteristic of the more abaundant black barren material but are definitely molybdenum-bearing.

The authigenic minerals calcite, kaolin, and pyrite are present wherever mining or surface drilling has enabled inspection of the Westwater Canyon Sandstone Member. The absence of a heavy mineral suite and the presence of corroded detrital feldspar grains, as described by Austin elsewhere in this memoir, has been noted but not investigated.

Pyrite ranges in abundance from about I to 4 percent. It is somewhat more common in sandstone impregnated by ore or barren material than in waste rock and is particularly abundant in high-grade ore. It occasionally forms thin, dense bands a few inches long and a fraction of an inch wide on ore boundaries or mudstone surfaces and within bodies of unusually high-grade ore. Pyrite crystals are common within mudstone clasts, where they occur as single crystals or small clusters, and attain a size of one to 5 mm. Pyrite crystals disseminated through the sandstone are usually a fraction of a millimeter in diameter and appear to "dust" the sandstone.

Kaolin ranges in abundance from less than r to more than 5 percent, probably averaging about 3 percent. It seems more abundant, however, because of its conspicuous appearance. Kaolin blebs or "nests" are larger and more abundant in coarse-grained rock and are equally abundant whether the host rock is bleached and barren, impregnated with ore, or impregnated with barren material. Several of the photographs included in this paper show these relationships clearly (pl. IA, IC). Neither pyrite nor kaolin has been observed to be coated or stained by ore or barren material.

Authigenic quartz is present as overgrowths on detrital quartz grains and is associated particularly with the streaky, molybdenum-bearing barren materials. Authigenic quartz probably comprises less than one percent of the total volume of the rock.

Calcite is sporadically distributed and does not seem to be greatly more abundant in a particular rock or mineral phase. It does tend to concentrate, however, at the base of sandstone units and at ore-waste contacts, particularly in thin, high-grade ore (0.50 to I.00 percent). In areas which are "luster-mottled," or filled by one fourth inch to one inch bodies of interstitial calcite in crystal continuity, the calcite generally encloses any ore-bearing or barren material. There is no constant relationship, however. Samples have been collected in which bodies of calcite about the size of marbles contain coatings of barren material on the enclosed sand grains, while the calcite-free areas contain no impregnating barren material. In one sampled locality, a similar relationship exists, except that most of the calcite-covered areas are devoid of internal coatings and a few contain coatings of barren material. The individual calcite bodies in this occurrence are rimmed by small kaolin blebs and enclosed in a matrix of ore material. In still another specimen, from a single isolated occurrence, the grains within the calcite crystals are free of impregnations, but the sandstone surrounding the calcite crystals is impregnated by barren material.

Along the northern side of the main ore body, in places a calcite "shell" has developed. This shell is one to four inches thick. It coincides with the border of the ore, forming a "nose" or backward C. The outer edge of this shell is sharp, abutting against low-grade rock. The inner margin is less distinct and is gradational through about one foot, from solidly calcite-impregnated sand into ore containing spotty, isolated, pea-sized calcite bodies. There is no ore material on the sand grains enclosed by the calcite of this shell. In one location, a double shell was observed (pl. 1-A). The shells were closely parallel and were separated by about one and a half feet of ore. A six-inch halo of low-grade ore material (0.10 to 0.15 percent) extended past the outer shell.

Several features or spatial relations between ore and black barren material have been observed. These are as follows:

I. the consistent parallelism of boundaries between ore and barren material and the peripheral location of patches of barren material with respect to ore, described earlier.
2. interstitial calcite bodies in a matrix of ore, containing sand impregnated by barren material.
3. a silicified tree trunk, with a halo of barren material and an outer halo of low-grade ore material.
4. a fracture, with a displacement of about one inch, offsetting filaments of barren material (pl. 1-F). The same fracture contains ore material and has a halo of ore around it. This is exceptional. Instances of faults offsetting both ore and barren material are more common.
5. a small mudstone-cobble conglomerate layer, with mudstone cobbles surrounded and impregnated by barren material. The layer is partly enclosed in ore but projects past the ore boundary into barren country rock.
6. isolated mudstone cobbles impregnated by barren material, but surrounded by ore.
7. lenses and filaments of black barren material enclosed by ore.
8. a small lens of dense black barren material, within a fine-grained sandstone bed, enclosed by ore, and cut by fractures limited, for the most part, to the fine-grained sandstone unit. Where the fractures cross the barren black lens, they are separated from the barren material by a "leached" zone a fraction of an inch wide. The fractures also contain ore material, even where they cross the barren lens (pl. i-E).
9. occasionally, mudstone cobbles or pebbles a few feet to a few dozen feet away from bodies of ore or barren material will nevertheless be impregnated or "haloed" by ore material or molybdenum-bearing material. The halos also occur on carbonized or silicified wood fragments. Where a number of pebbles occur together, some may contain impregnations, even though adjacent pebbles appear unaffected.

## ACCESSORY ELEMENTS

In addition to megascopically recognizable minerals or minerallike material, varying quantities of molybdenum, vanadium, and selenium occur in association with the ore barren phases. Their exact mode of occurrence has not been established at the Ann Lee mine. Molybdenum, as mentioned previously, is preferentially concentrated in both types of black barren material. Samples of the barren material

## DESCRIPTION OF PLATE

### PLATE 1. Views of Underground Ore Faces

A Double shell of calcium carbonate. The inner shell (near scale) corresponds to the boundary of the main ore body over several tens of feet in section; the outer shell to the boundary of a small, local patch of ore. A zone of about six inches of sandstone outside the outer shell also contains a little uranium-bearing material. The faint, wormlike forms inside the inner shell are unexplained, but are suggestive of leaching.

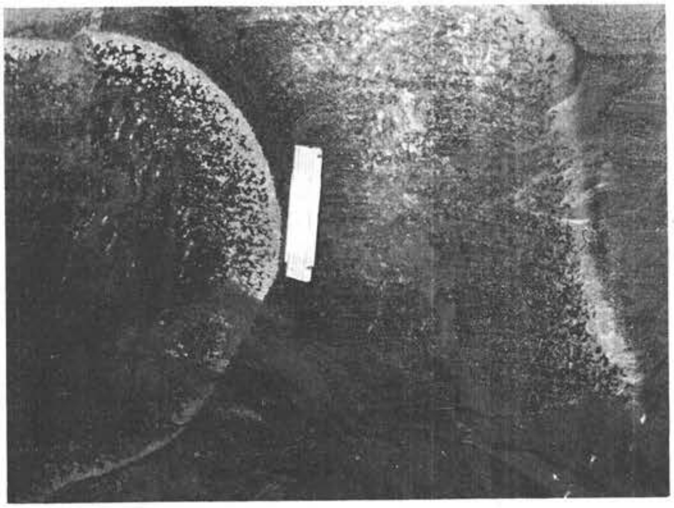
B View of ore boundary, cutting across fine-grained, thin-bedded sandstone. View looking east, near northern edge of main ore body.

C Slightly distorted mudstone clast, showing mineralized halos and association of kaolin (white patches) with the coarser sandstone beds.

D Typical view of ore (below) and banded black barren material (above). Note fading edge of ore (at hammer handle). The parallelism of the boundaries and the intervening zone of light-colored, unimpregnated sandstone are characteristic.

E Black, barren lenses enclosed by ore. The barren lenses are cut by fractures. These are filled with uranium-bearing material which is constricted in the fracture where it crosses the black barren lens.

F A system of small fractures which offset black, barren material (upper left) but which influence the shape and distribution of ore (bottom and right). "Ghost" boundaries within ore at bottom suggest reworking.



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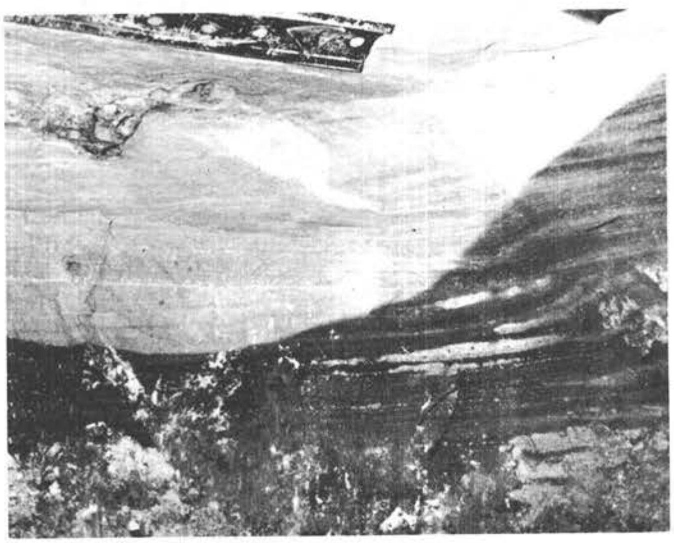

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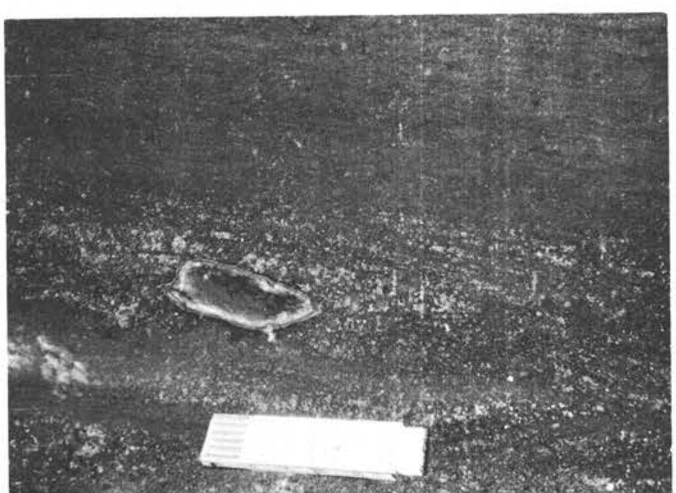

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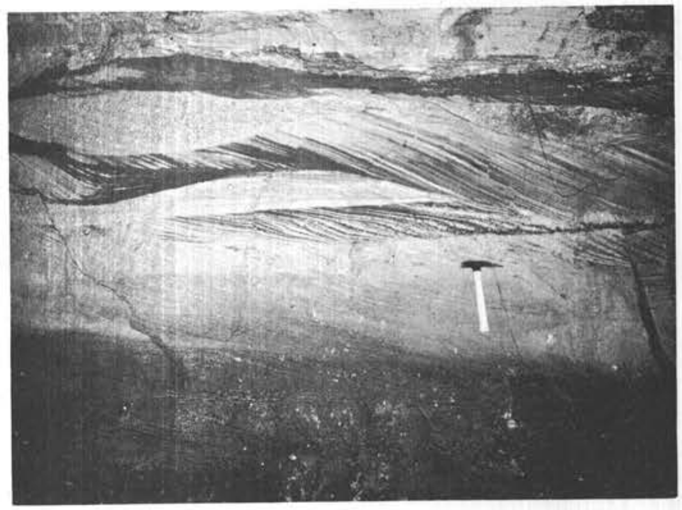

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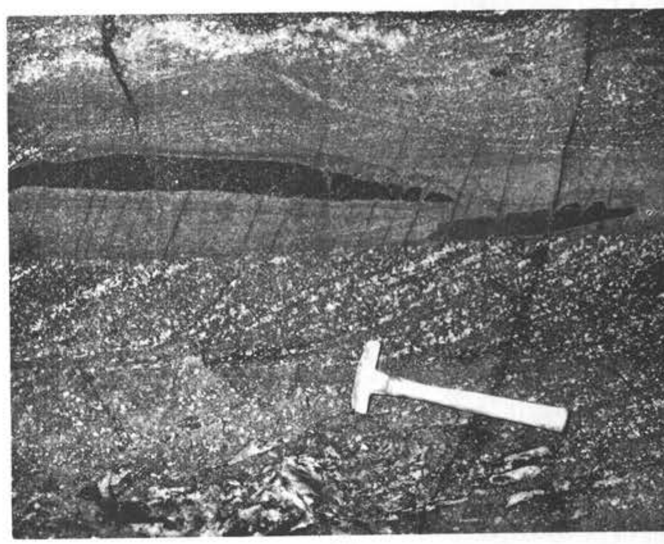

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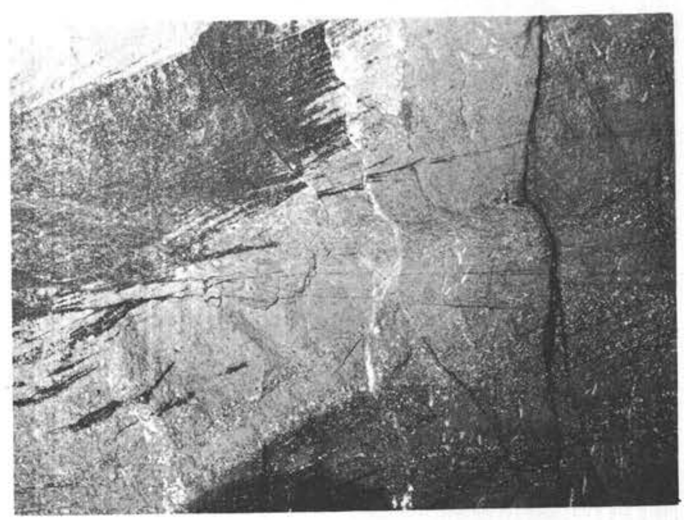

F

range from 0.10 to 0.36 percent Mo. Molybdenum is also present in the ore, but in much smaller amounts. About 15 samples of ore were tested for molybdenum. The results were all in the range o.oz to o.00z weight percent.

Vanadium is present in both ore and barren material. In the ore, the amount of vanadium increases as the grade of ore increases, but not proportionally. Ore containing 0.20 percent $U_30_8$ generally contains about 0.10 percent $V_20_5$, whereas ore containing 3.00 percent $U_30_8$ generally contains about 0.50 percent $V_2O_5$. Vanadium has been found in amounts varying from o.03 to 0.20 per cent $V_20_5$ in barren material, but too little sampling has been done to permit any conclusions regarding relative distribution. The sample which contained 0.20 percent $V_2O_5$ was from a lens surrounded by ore and was probably contaminated.

The concentration of selenium is quite low, both in ore and barren material, but it does appear to be more abundant in the barren material. The average selenium content of the ore is about 0.005 percent; of the barren material 0.02 percent.

## SPECIAL FEATURES

Certain features of the Ann Lee ore deposit suggest that at least two fluids, of somewhat different compositions, contributed to the alteration of the Westwater Canyon Sandstone Member and the deposition of the ore and associated minerals. The most obvious of these features is exhibited both by ore material and barren material and consists of sharp, arcuate, concave or convex boundaries which cut across sedimentary structures and minor lithologic boundaries. The boundary curve is often smooth and regular and apparently is completely independent of differences in the permeability of the host rock. This boundary is interpreted as a fluid-fluid interface, since the writer cannot visualize any other reasonable set of conditions which might produce such a surface.

The carbonate shell described earlier also suggests a fluid-fluid interface, with calcite being precipitated at the interface by a difference in pH, or temperature, or some other fluid characteristic, presumably at a time when the interface was static.

Occasionally, isolated mudstone clasts have an asymmetric halo of ore material. Wherever this feature has been recognized, the halo has been elongated toward the southeast, suggesting a west-to-east movement of the depositing fluid. An even more impressive bit of evidence was provided by a section of silicified log near the main ore body. This log had a thin halo of barren material with a teardrop shape, surrounded by a second, similar halo at low-grade ore material. The "tail" in this instance also pointed east.

At the time the main Ann Lee ore body was first opened by mine workings, the level of water saturation coincided with the top of the ore at a point a few hundred feet northwest of the shaft. West of that point, except for a few small bodies of perched water, the ore was dry. This ore exhibited differences, of degree rather than of kind, from ore in the water-saturated zone. Chief among these differences were a predominance of light to medium brown ore with wide, fading boundaries, relatively abundant examples of fractures and small faults influencing ore distribution, and a relative scarcity of black barren material. "Ghost" boundaries, or boundaries within the ore, marking the contact of areas of appreciably different grade were occasionally noted, along with a patchy or sometimes mottled appearance of the ore and sometimes faint, wormlike or indeterminate forms within the ore. In general, these features are interpreted as the results of leaching of a previously high-grade ore body. Whether or not their relation to the recent water surface is significant has not been established, but the presence of kaolin and pyrite superimposed on the ore and unstained would seem to indicate that reworking of the ore was a discrete event, completed prior to the deposition of kaolin and pyrite and not repeated since. Perhaps it should be repeated here that the "reworked" ore is, nevertheless, the same type of material as the rest of the ore. There are no premine oxidized minerals and no evidence of oxidation anywhere in the Ann Lee mine, other than the rare red mudstone clasts described before.

## SUMMARY AND CONCLUSIONS

The peripheral relation of barren material to ore may reasonably be interpreted as evidence that the ore in such a place is at least slightly older than the barren material, since it seems unlikely that the barren material was deposited in a consistent pattern surrounding empty sandstone and that the void was subsequently neatly occupied by ore. Much of the evidence cited in the section of this paper dealing with spatial relationships, however, strongly implies the opposite age relationship. This contradition may be resolved by assuming that the ore has been partly leached and redeposited subsequent to the development of the barren material. The assumption is supported by the relation of ore to fractures, as described previously, and by the findings of geologists of other mines in the district. The mechanism by which the ore and barren material are developed in such close association, and yet in such distinct, separate phases, however, has yet to be explained. The writer tentatively accepts the view that the earliest ore and the barren material were essentially contemporaneous and were separated by differences in their physical and chemical character during migration from some common source. At least part of the ore is younger than the barren material, and at least part of the ore was deposited from solutions migrating from west to east. If the dark ore with sharp boundaries and peripheral barren material is an older generation of ore, then a considerable portion of the Ann Lee ore deposit has been reworked or subjected to varying degrees of leaching, mobilization, and redeposition. It is curious that the ore deposit has retained such distinctive orientation and continuity, as well as generally sharp boundaries and close relation to stratigraphy, features in the Ambrosia Lake area that are generally considered at least suggestive of primary or "first generation" ore.

The writer also finds it difficult to visualize a fluid capable of corroding feldspars and depositing kaolin, yet so chemically ineffective that it only rarely alters even very small fragments of mudstone, unless they have been previously subjected to mechanical deformation.

The kaolin has been logically supposed to be indicative of acid solutions (Austin, this memoir); yet, it has been found associated with uncorroded calcite bodies in a textural pattern which certainly suggests that it is later than the calcite, and, therefore, presumably deposited from solutions in or near equilibrum with the calcite.

Aside from the statement of their existence, little or nothing is known concerning the two fluids implied by the inter face features. Whether the difference was of temperature, pH, oxidation potential, chemical content, or all of these has not been established, to the writer's knowledge.

It appears that knowledge concerning the origin and depositional environment of the Ann Lee and related deposits is, at best, incomplete.

# *Geology and Ore Deposits of the Sandstone Mine, Southeastern Ambrosia Lake Area*

GARY F. HARMON AND PAUL S. TAYLOR

## INTRODUCTION

The Sandstone mine is in sec. 34, T. 14 N., R. 9 W., McKinley County, New Mexico (fig. 1, *Hazlett and* Kreek, this memoir).

Surface drilling on this section was initiated in February 1956, and a major ore deposit was discovered and partially drilled out by the end of the year. Additional drilling conducted during 1957 and 1958 showed that the deposit was comprised of separate ore bodies in a belt covering the middle one third of the section and extending from the east to the west section lines. Subsequent drilling showed the ore to be continuous with the ore bodies of the adjoining east and west sections.

## STRATIGRAPHY

The Morrison Formation in section 34 is subdivided into the Recapture Member, Westwater Canyon Member, and the Brushy Basin Member with a total average thickness of 425 feet.

At the Sandstone mine, the Recapture Member averages I 10 feet in thickness and consists of interbedded mudstone, siltstone, and fine-grained sandstone. Where exposed in the mine workings, the Recapture Member is a green, calcareous mudstone interbedded with gray-white, fine-grained sandstone. The Westwater Canyon Member overlies the Recapture Member. The contact is not well defined because of the characteristic intergrading of the members.

The Westwater Canyon Member averages zoo feet in thickness in section 34 and consists of fine- to coarse-grained sandstone and mudstone. The sandstone has been divided into five distinguishable units designated A, B, $B_1$, C, and D in ascending order. These units range in thickness from 12 to 6o feet and are separated by green mudstone units which range in thickness from 2 to 18 feet. The sandstone is predominantly fine-grained and is characterized by fluvial cross-bedding; however, scours filled with coarse-grained sandstone are prominent. Mudstone cobbles commonly occur within the coarser-grained channels.

The contact of the Westwater Canyon Member with the overlying Brushy Basin Member is well defined and does not exhibit an intertonguing relationship. The Brushy Basin Member averages 115 feet in thickness and consists of green calcareous mudstones interbedded with siltstones and fine-grained sandstones.

## STRUCTURE

The most prominent structural feature of section 34 is the graben in the western half of the section. The major faults of the graben are parellel normal faults, striking N. 10 E. and dipping 6o to 7o degrees east and west, respectively. The faults are 500 feet apart at the Recapture—Westwater contact. Where intersected by mine workings, displacement is 40 feet on the east fault and 55 feet on the west fault. Surface drill-hole data indicate decreasing displacement to the north. The east fault was relatively dry and tight; the brecciated zone of the fault was three feet wide. The west fault was extremely wet with the brecciated zone similar in width. The increase in the amount of the water along the west fault is interpreted as an interruption of the downdip flow of ground water. The workings within the graben are dry, while those to the west of the graben are relatively wet, supporting this interpretation.

A zone of minor faulting extends east of the graben for 42 feet. The faults within this zone are high angle and parallel the graben. Displacement ranges from two inches to two feet. This fault pattern is also present on the western side of the graben (fig. i ).

Other normal faults with displacements of one to six feet are also associated with and parallel to the major graben faults. These faults are found up to i 000 feet east and west of the graben. Relative movement of the faults, as indicated by bed offset and slickensides, is normally dip-slip. However, some evidence of slight strike-slip movement has been observed.

Fractures are numerous throughout the mine workings. The fractures strike N. 15 E. to N. 15 W. with dips ranging from 65 degrees to vertical.

Another significant structural feature is the change in attitude of the beds near the east section line. The dip changes abruptly from the normal 2 to 3 degrees northeast to greater than 7 degrees east (fig. 5, *Hazlett and Kreek,* this memoir).

## MINERALOGY

The principal uranium mineral has been identified as coffinite. It is closely associated with the dark carbonaecous material and coats and impregnates the sand grains. The only alteration product of coffinite noted is efflorescent zippeite which forms in the older, well-ventilated mine workings in the higher-grade ore bodies.

The vanadium minerals have been identified as montroseite and paramontroseite. These minerals are found in uranium-deficient sandstone as well as within .the ore bodies. Efflorescent pascoite is present in the older mine workings. Jordisite has been identified as the major molybdenum mineral and is generally associated with the black barren material. Ilsernannite, an alteration product of jordisite, has been noted in the older and drier mine workings.

Assays of ore shipments show an average of 0.005 percent selenium. A silver-gray mineral which resembles thin films of aluminum foil commonly occurs along planes of movement within fractured mudstone cobbles. This mineral has been tentatively identified as native selenium. It occurs in the mudstones within the ore bodies as well as in mudstones outside the ore bodies.

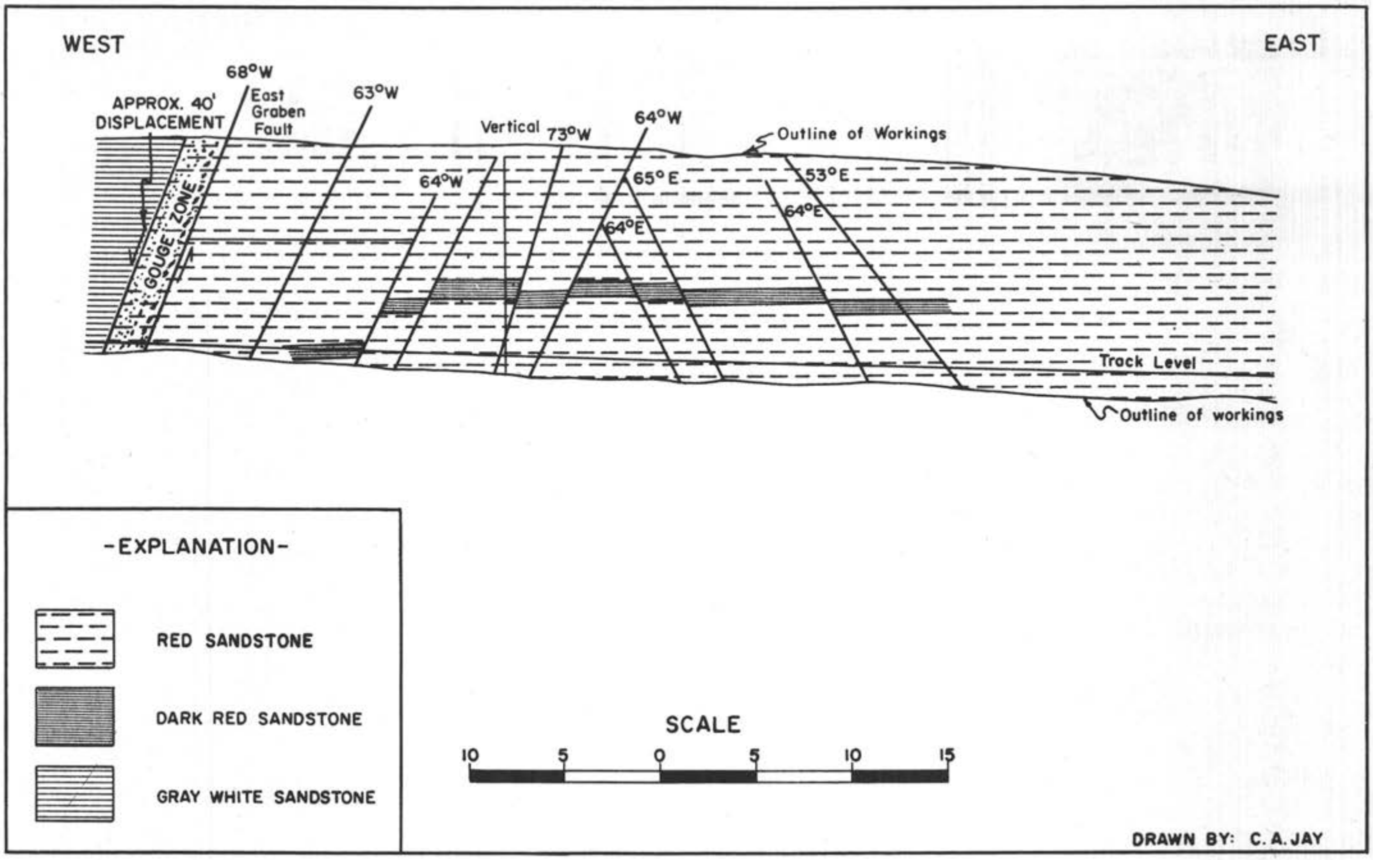


Figure 1

Sandstone mine, section 34, T. 14 N., R. 9 W.
Rib map looking north at intersection of east side of graben.

Nonmetallic accessory minerals associated with the ore are calcite, barite, and kaolin. Of the three, calcite is the most abundant. It occurs as a cementing material in the sandstone and is generally concentrated near the base of the sandstone unit. Crystalline calcite is often observed along fracture planes.

Tabular crystals of honey-yellow barite have been found along fracture planes in the D ore zone. These crystals are extremely radioactive.

Kaolin occurs throughout the Westwater Canyon Sandstone as small white blebs. In the coarser-grained sandstone, the blebs are larger and more noticeable.

The only metallic accessory mineral associated with the ore is pyrite. It occurs as disseminations throughout the bleached sandstone and is commonly concentrated along fracture planes, around mudstone cobbles and lenses, and at the base of the higher grade ore bodies.

## ORE DEPOSITS

Ore bodies at the Sandstone mine occur in each of the five sandstone units or zones. These zones are separated and defined by discontinuous mudstone units. The ore bodies occur in alternating zones, for example, where the A and C zones contain ore in the same vertical section, the intervening B zone is barren. Where ore bodies are present in the B and D zones, the intervening C zone is barren. The noted exception is in the eastern part of the section where the $B_1$ and C zones contain ore bodies.

The ore bodies have continuity along trend with a marked lack of continuity across trend. Usually the northern edges of the ore bodies are sharp, roll contacts with the barren rock. The southern boundaries grade from black to light brown into barren rock. This gradation is usually accompanied by a decrease in thickness of the ore.

The ore bodies tend to occupy a higher stratigraphic position to the north as opposed to the regional dip (fig. 2).

The grain size of the sandstone apparently has little effect on the deposition of ore. Ore occurs in sandstone ranging from fine-grained to conglomeratic and is seldom affected by lateral changes in grain size. Generally, the ore in finer-grained sandstone is higher grade than ore in the coarser sandstone. Uranium tends to localize around mudstone cobbles and lenses forming high-grade ore halos (fig. 3). The ore impregnates distorted, deformed, and fractured mudstones.

Two types of carbonaecous material are associated with the ore deposit. The first type was formed from alteration of fossil wood, bone fragments, and accumulations of organic trash. The second type occurs as coatings on sand grains and fills pore spaces. At the Sandstone mine, the first type has no effect upon deposition of ore; however, where this detrital material is present within an ore body, this materal contains high

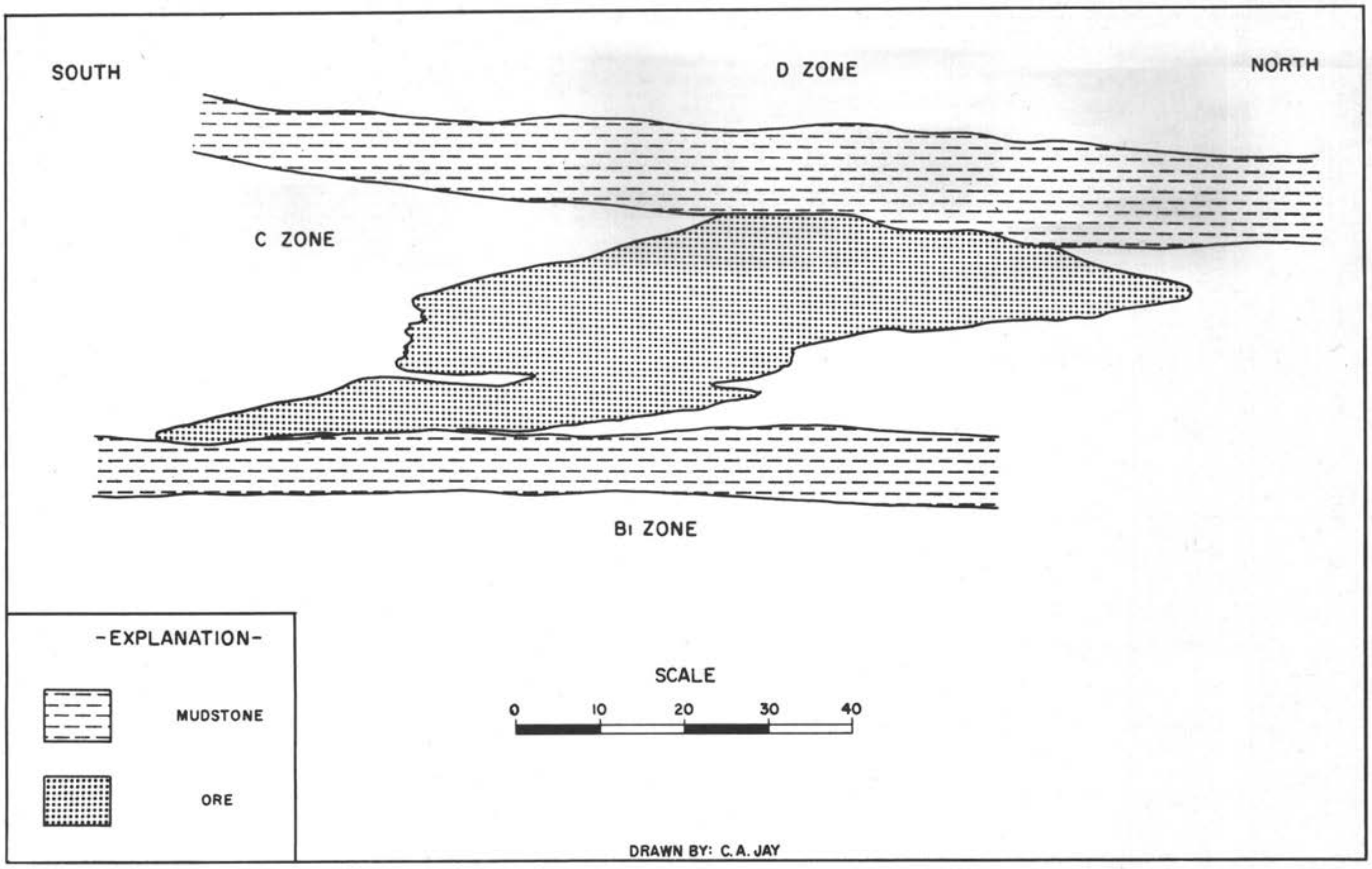


Figure 2

SANDSTONE MINE, SECTION 34, T. 14 N., R. 9 W.
Section through C; zone showing ore stratigraphically higher on north side of ore body.

concentrations of uranium. The second type of carbonaceous material is intimately associated with the uranium mineralization. The color of ore varies from medium brown to black, depending upon the amount of carbonaceous material present. This provides a visual guide to uranium content; that is, the darker the color, the higher the grade of the ore. Results of chemical tests verify that the uranium content increases as the organic carbon content increases.

In general, the relationship of the vanadium content with the carbonaceous material is the same as that of uranium. The noted difference is that in the lighter-colored ore bodies (lower grade), the ratio of vanadium to uranium is higher than in the blacker or higher-grade ore bodies.

Representative samples from ore bodies within each zone were assayed to determine the uranium-vanadium ratio. In the higher-grade ore bodies, the uranium-vanadium ratio is 2.77:1. In the lower-grade ore bodies, the ratio of uranium to vanadium is i.19:1.

There is an abundance of black material which resembles the ore but is deficient in uranium. Tests conducted on this material by Elmer Santos, of the U.S. Geological Survey (written communication), indicate the absence of organic carbon. The over-all composition of this material is not known; however, it is known to contain molybdenum and probably vanadium. Because of its uranium deficiency, it is referred to as black barren material.

There are two distinct types of black barren material, each of which maintains a separate relationship with the ore. Both types resemble ore in appearance and form but are usually distinguishable by luster, contact, and associated accessory minerals.

The most abundant type occurs as masses and streaks usually separated from the ore bodies both laterally and vertically by two to five feet of barren white sandstone. Where the black barren material is contiguous with ore, the contact is difficult to distinguish. The contact between the black barren material and the surrounding barren rock is a distinct black to white color change. This contact has a "feather" appearance as a result of the black barren material being deposited along thin bedding planes of higher permeability.

This type is sometimes characterized by quartz overgrowths which give rise to a sparkling reflection. In the A zone, this material completely surrounds the ore bodies with the greatest concentrations along the lateral boundaries. In the C zone, this type is present along the top and sides of the ore bodies but the sill is relatively free of this material. The B and $B_1$ zones contain this type, but to a lesser extent than the A and C zones.

The second type of black barren material appears as lenticular pods concentrated in the upper parts of the ore bodies and in the barren sandstone above the ore-waste contact. These pods never contain quartz overgrowths. They are usu-

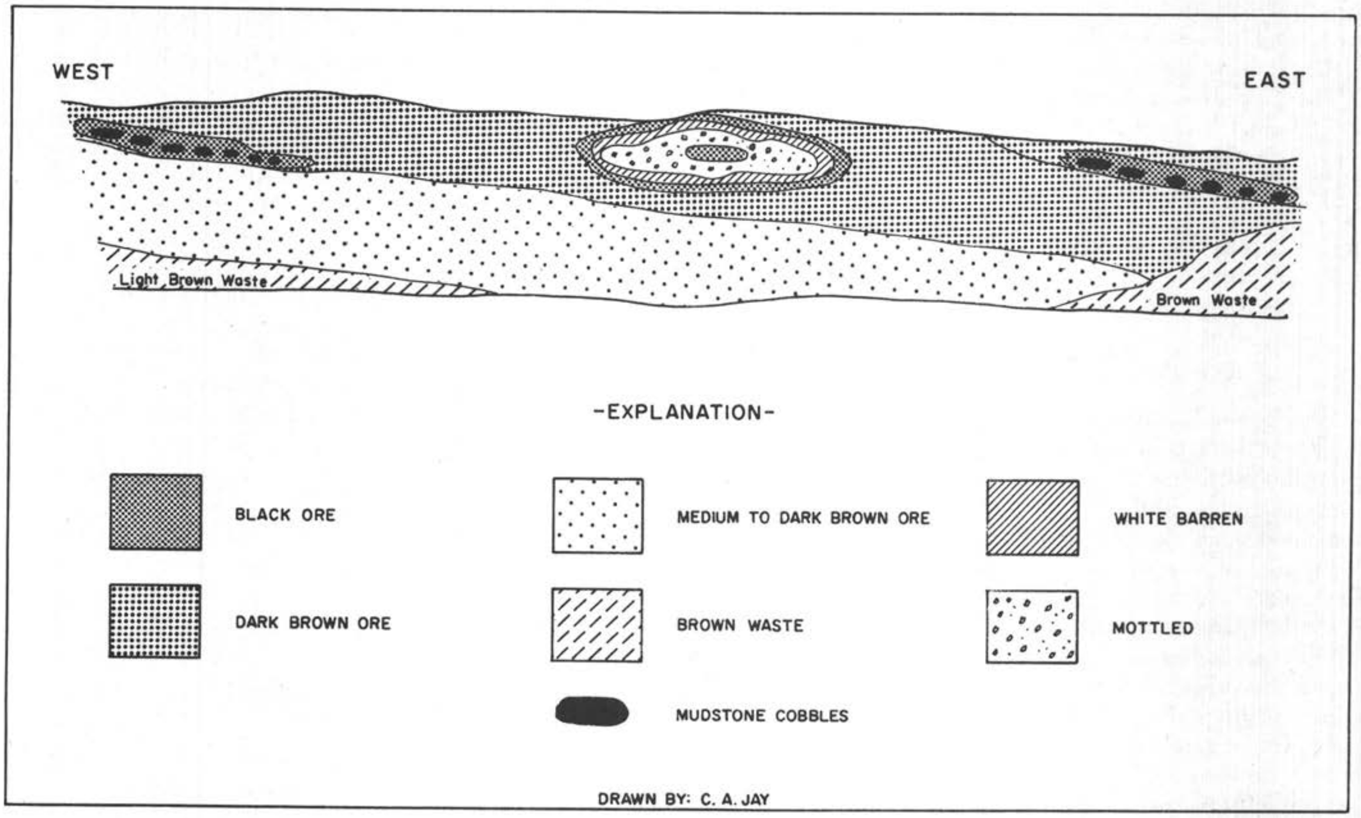


Figure 3

Sandstone mine, section 34, T. 14 N., R. 9 W.
Generalized section showing high-grade halos around mudstone cobbles and calcite shells.

ally black with a pitchy luster similar to that of high-grade ore. They possess smooth, curving boundaries and have rims of pyrite from 1/32 inch to 1/4 inch wide. They are elongated in the direction of the ore trends with their long dimensions seldom exceeding three feet and vertical dimensions ranging from one inch to one foot. This type is also more common to the ore bodies of the A and C zones than the ore bodies of the B and $B_1$ zones.

The D zone exposed in the present mine workings is entirely void of either type of black barren material.

Highly concentrated masses of calcite occur within the ore bodies and are surrounded by a thin halo of high-grade ore. The outer ring of the shell is composed of calcite and bleached sandstone. This grades into a ring where black ore occurs as patches producing a mottled texture. The center is composed of black ore (fig. 3).

## A ORE ZONE

The A zone is the lowermost of the five stratigraphic zones of the Westwater Canyon Member. In section 34, this zone averages 6o feet in thickness. It is a fine- to medium-grained, poorly cemented sandstone and contains mudstone cobbles and some thick, continuous mudstone lenses.

There are three main ore bodies within the A zone, one to the west of the graben which is continuous with the ore body of section 33 and two parallel ore bodies in the eastern half of the section. These two ore bodies converge near the east section line and can be traced eastward into section 35. All these ore bodies are confined to the lower half of the A zone. The ore bodies consist of parallel elongated pods which tend to overlap vertically and coalesce laterally, causing extreme variations in vertical thicknesses along trend as well as across trend. Individual pods range in width from a few feet to many tens of feet. Where these pods overlap, vertical thicknesses in excess of 20 feet have been observed. These pods are controlled by mudstone conglomerate lenses and channels of higher permeability. Satellite ore pods occur north and south of the main A ore bodies. These isolated pods have widths of less than 15 feet.

## B ORE ZONE

The B sandstone overlies a thick, continuous mudstone unit which is used as a reference for separating the A and B zones. It underlies a thin mudstone unit separating the B and $B_1$ zones. The average thickness of the B zone is 4o feet.

The B sandstone is medium- to coarse-grained and contains numerous mudstone cobbles and thin, discontinuous mudstone lenses. This zone contains cross-bedding and scourand-fill channels. The ore transects the cross-bedding and channels.

This ore zone contains the greatest thickness of ore in the section. The ore lies directly on the basal mudstone unit and in some areas occupies the full thickness of the zone. The main ore body trends N. 71 W. The width ranges from 4o to 15o feet and the length is in excess of 1200 feet.

No satellite ore pods are present to the north of the main ore body; however, a strongly mineralized zone extends south of the ore body and in places ore pods occur within this zone.

The B sandstone contains several fractures and fracture sets. Normal faults of small displacement are commonly associated with the fracture sets. Displacement along the faults never exceeds two inches. The faults and fractures strike from N. 15 E. to N. 15 W. and dip 65 degrees to vertical. Where observed, these faults offset the ore. No relationship has been noted between the fractures and ore deposition.

## $B_1$ ORE ZONE

The $B_1$ sandstone is underlain and separated from the B sandstone by a thin mudstone unit. It is usually separated from the overlying C zone by a mudstone unit. This zone averages 20 feet in thickness and is a medium-grained, well-cemented sandstone containing abundant mudstone cobbles. Very large angular mudstone remnants, one of which was ten feet square and 20 feet long, have been observed. This zone is relatively free of fractures.

The ore bodies in this zone are very discontinuous and spotty and vary in cross-sectional areas. They rarely exceed 5c feet in width and are elongated in an east-west direction and range from six feet to 20 feet in thickness. The grade of the ore is extremely variable but is generally low grade. The ore in this horizon conforms to, and lies on, the irregular surface of the underlying mudstone.

Along the eastern part of the section, the mudstone unit separating the $B_1$ and C zones is thin and discontinuous. Where the mudstone is not present, the ore bodies in these zones combine and become one ore body and attain a thickness in excess of 5o feet. Where this occurs, the ore bodies of each zone retain their identity and can be separated by differences in grade.

## C ORE ZONE

The C zone averages 25 feet in thickness and is predominantly a coarse-grained well-cemented sandstone. It is the most cross-bedded zone in the Westwater Canyon Member. Individual channel sands seldom exceed ten feet horizontally or one foot vertically. Within individual channels, sand grains range in size from fine to very coarse. This type of channel is predominant; occasionally, however, channels of very fine- to fine-grained sandstones are found in this zone.

The western end of the main ore zone is made up of two distinct ore bodies. The southern ore body lies upon the basal C mudstone unit. The northern ore body occupies a higher stratigraphic position in the sandstone unit and in places the edges overlap. The average thickness of the individual ore bodies is eight feet. Where the overlap occurs, the ore attains a thickness of i6 feet.

The ore bodies converge to the east forming one ore body that averages 6o feet in width and extends along trend more than 2000 feet (fig. 2).

## D ORE ZONE

The D zone is between the underlying D mudstone and overlying Brushy Basin Member. This zone is 20 feet thick and is generally a fine-grained sandstone. There are two known ore bodies within the D zone in section 34. One is on the western side of the section, and the other is in the eastern part of the section. The D ore developed along the east side of the section is in three horizons in the sandstone; elongated in an east-west direction on the D mudstone, elongated in a west-southwest direction in the middle of the sandstone unit, and elongated east-west directly under the Brushy Basin Mudstone. Minor faults in this sandstone offset the ore.

Ore bodies in contact with the Brushy Basin Mudstone and the D mudstone unit are high grade. Ore thickness ranges from two to four feet with widths of 7o to 8o feet. This ore is in a fine-grained sandstone which does not contain mud-stone cobbles or lenses. The bodies are relatively flat-lying against the overlying and underlying mudstones.

The middle ore horizon is six to eight feet thick and is lower in grade. The ore in this horizon is only 2o to 4o feet wide but extends more than 800 feet in length. This horizon contains occasional mudstone cobbles and lenses around which the ore is localized.

# SUMMARY AND CONCLUSIONS

The ore bodies at the Sandstone mine are elongated in an east-west direction and follow depositional trends.

Ore is intimately associated with carbonaceous material. Chemical tests show that uranium content increases as the organic carbon content increases.

A major control of ore deposition within a zone is the relative thickness of the sandstone. Where the sandstone attains a greater than normal thickness, the ore body increases in thickness and is higher grade. The ore bodies also increase in thickness where the intervening mudstone unit between zones is not present, forming a thicker vertical sandstone section.

In general, the ore bodies occupy a position stratigraphically higher in the sandstone zones as they are traced downdip to the north. The ore bodies tend to maintain a horizontal datum plane, suggesting that deposition of ore was controlled by a fluid interface.

Mudstone cobbles and thin mudstone lenses within the ore horizons affect the deposition of ore. The ore immediately adjacent to these features is higher grade. These mudstones are surrounded by a halo of high-grade ore and where deformed, fractured, and distorted, they are impregnated with ore. The mudstone cobbles and the large irregular mudstone blocks are remnants of pre-existing mudstone units.

Different uranium-vanadium ratios of the ore bodies indicate secondary migration and redeposition of some of the ore. The ore bodies that have a uranium-vanadium ratio near or greater than 3: I are considered primary ore bodies. They are higher grade, dark black in color, and generally have thicknesses less than ten feet. All the ore in the D, C, and southern A zones is considered primary ore.

The ore bodies that have a uranium-vanadium ratio near 1:1 are considered redistributed ore bodies. They are characterized by low-grade ore, a light brown color, and are generally thicker than the primary ore bodies. Ore in the $B_1$, B, and northern A zone is considered to be redistributed ore.

Black barren material is associated with the ore deposits. It occurs as two types, massive and lenticular. The massive type is peripheral to the ore body. It is extensive around the C and the higher grade parts of the A and B ore bodies and is present to a lesser extent around the lower-grade ore.

The lenticular type is present both as peripheral lenses to ore and within ore. This type is generally in the upper parts of the ore bodies. Compared to the massive type, the lenticular type does not display a definite relationship to grade of ore.

The only red sandstone encountered in the mine workings is in the lower half of the A zone. This red sandstone extends eastward 700 feet from the graben and appears to have been offset by the east graben fault. No uranium has been encountered in this red sandstone.

No relationship has been noted between fractures and ore deposition. Where observed, faults associated with these fractures offset the ore. At this time, the major graben faults have not been intersected in an ore zone; therefore, the relationship between ore deposition and this faulting is not known; however, the secondary minor faults near the graben offset the ore.

# *Geology and Ore Deposits of the Cliffside Mine, Ambrosia Lake Area*

**DEAN S. CLARK AND STUART R. HAVENSTRITE**

## INTRODUCTION

The Cliffside mine is in the SW1/4 sec. 36, T. 14 N., R. 9 W., McKinley County, New Mexico *(Hazlett and* Kreek, fig. 1, this memoir). The Cliffside ore deposit is the easternmost ore body that has been developed in the South Ambrosia trend. Another deposit has been partly explored by surface drilling near the east quarter corner of section 36, on the Middle Ambrosia trend. This deposit is not considered mine-able at present.

Phillips Petroleum Company, operator of the Cliffside mine, conducted an exploratory drilling program in 1956 and 1957. Commercial ore was discovered, and a circular, concrete-lined shaft, 12 feet in diameter, was started in May 1958. The mine station was excavated at a depth of 1429 feet (elevation 5642 feet), and the shaft was completed to 1497 feet in February 196o. Ore production began in October 1960.

## GENERAL GEOLOGY

### STRATIGRAPHY

Formations penetrated by drilling from the surface range in age from Jurassic to late Cretaceous. The oldest formation intersected is the Jurassic Bluff Sandstone, which has an estimated thickness of 25o feet. The Bluff Sandstone is conformably overlain by the Morrison Formation, which is subdivided from bottom to top into three members: the Recapture Member, about loo feet thick; the Westwater Canyon Member, 15o to 225 feet thick; and the Brushy Basin Member, 125 to 90 feet thick. The variation in thickness of the upper two members is mainly due to intertonguing at their contact; the aggregate thickness ranges from 325 to 375 feet.

The Recapture member consists of greenish gray and red mudstone, red silty sandstone, and local lenses of light gray, fine-grained, well-sorted sandstone.

The Westwater Canyon Member, which contains the Cliffside deposit, consists of fine- to coarse-grained feldspathic sandstone interstratified with thin beds of greenish gray mudstone. Sandstone constitutes about 85 percent of the member in section 36. The sandstone is predominantly gray, although red sandstone is common at and near the periphery of ore bodies. The sandstone locally contains abundant lenses and galls of greenish gray and red mudstone.

The Westwater Canyon Member has been subdivided into five sandstone units or zones in the eastern part of the Ambrosia Lake area *(Hazlett and* Kreek, this memoir). The zones are typically separated by mudstone beds. The upper half of the member, including from bottom to top the $B_1$, C, and D zones, is mineralized in section 36; the lower half is barren. The $B_1$ and C zones, each about 20 feet thick, contain all the known ore. They are lithologically similar, consisting of fine- to coarse-grained feldspathic sandstone. The C zone locally channels through the underlying mudstone bed into the $B_1$ zone, thus forming a combined sandstone bed about 5o feet thick. The D zone, which contains mineralized rock but no known ore, is finer grained and more silty than the $B_1$ and C zones. It has a maximum thickness of 15 feet and in places is missing. The mudstone bed separating the C and D zones is locally absent, especially in the southern part of the southwest quarter of the section.

The Brushy Basin Member consists of greenish gray, bentonitic mudstone and siltstone, sparse red mudstone and scattered lenses of fine- to coarse-grained feldspathic sandstone.

The Morrison Formation is disconformably overlain by 5o feet of Cretaceous Dakota Sandstone, which is in turn overlain by 105o feet of Cretaceous Mancos Shale and 120 feet of Cretaceous Gallup Sandstone. The Gallup Sandstone has been eroded and replaced in the southwest quarter of section 36 by as much as loo feet of alluvium, in which the Cliffside shaft is collared. In the northern part of section 36, the Gallup Sandstone is overlain by the Dilco Member of the Cretaceous Crevasse Canyon Formation.

## STRUCTURE

The regional dip of sediments in the Ambrosia Lake area is northeasterly. In most of section 36, the formations dip northwest two to three degrees. This anomalous direction of dip is the result of sag along the San Mateo fault *(Hazlett and Kreek,* fig. 5, this memoir). The beds form a broad, north-plunging anticline near the southeastern corner of the section; east of the fold, they again conform to the regional dip.

Two joint sets have been mapped in the Cliffside mine; one set strikes northeast, the other north. The joints are commonly filled with black material in or near the ore body. Other joints of the same set in the immediate area may be barren. Both joint systems are believed to be Tertiary in age. Rapaport (oral communication) has suggested that the northeast-striking joints predate the north-striking joints.

### SANDSTONE PIPES

Sandstone pipes are locally abundant in the Grants region. Hilpert and Moench 196o, p.441-442) described pipes in the Summerville and basal Bluff Formations, and in the Morrison Formation, in the Laguna district. The pipes are vertically oriented cylinders of re-sorted sandstone within relatively fiat-lying, bedded sandstone. According to Hilpert and Moench, "the material at any point in a pipe consists of the same material that forms the wall rock a short distance above, but it has been disaggregated and shows little or no bedding or other sedimentary feature." The Summerville pipes terminate in the lower Bluff Sandstone, while the Morrison pipes do not extend upward into the Dakota Sandstone.

Hilpert and Moench believe the pipes formed during accumulation of the highest beds they cut, before the containing beds were completely lithified. Rapaport, Hadfield, and Olson (1952, p. 39), in discussing the Summerville pipes, stated "the pipes probably formed by the slumping of blocks of poorly consolidated sandstone along planes of weakness which developed during diagenesis." They believe the pipes may be related to the primary folding and plastic deformation of the underlying Todilto Limestone. The pipes in the Laguna district have two consistent features—the contained sediments have been displaced downward, and stratification planes are nearly or completely obliterated.

Several Summerville pipes, similar to those found in the Laguna district, have been observed in the southern part of the Grants district. The only known Morrison pipes in the Grants district are at the Cliffside mine (fig. ) and the Doris mine (Rapaport, this memoir). While the sediments in these pipes have been downthrown, there has been no disaggregation and no destruction of bedding planes.

The South Cliffside pipe (fig. 2) is defined by surface drill holes, intersected by a track haulageway, and several dozen long holes drilled from the haulageway. The bounding ring

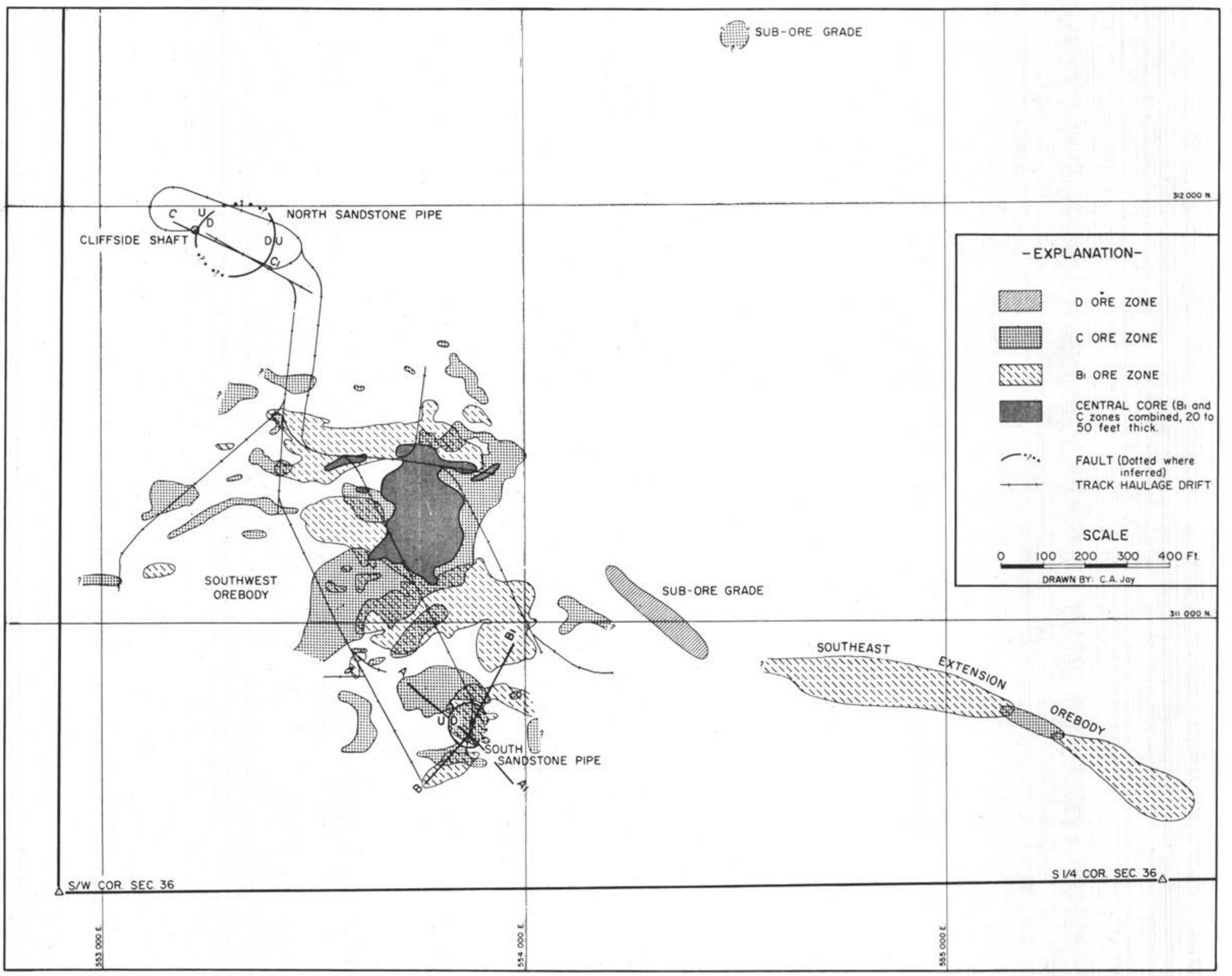


Figure 1

Cliffside mine, SW¼ section 36, T. 14 N., R. 9W.

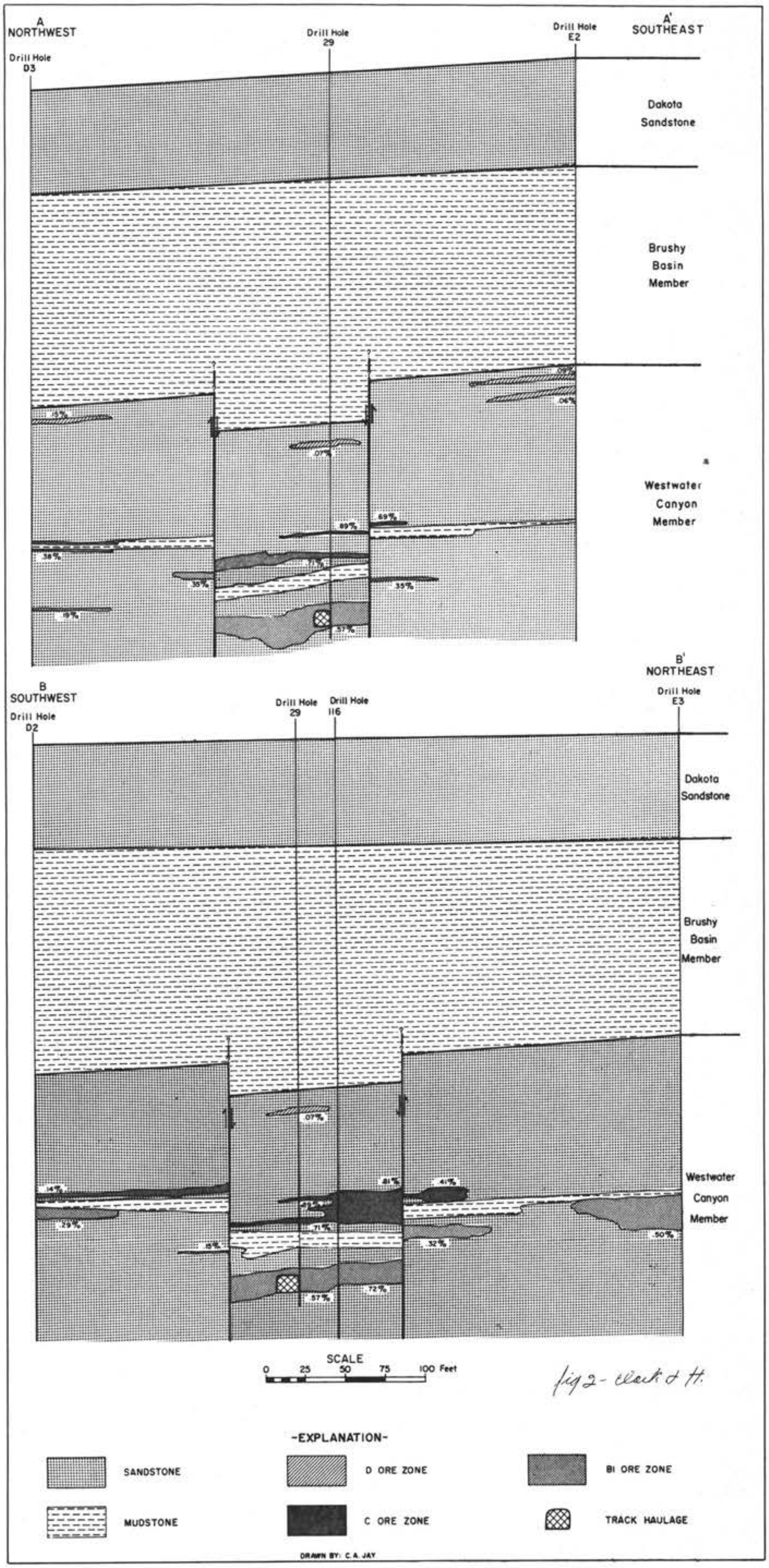


Figure 2

GEOLOGIC SECTIONS THROUGH SOUTH SANDSTONE PIPE, CLIFFSIDE MINE fault is a sharp vertical fracture which shows little associated shattering and, at most, a few inches of gouge. No brecciation has been observed within the structure, although there is minor slumping locally. All units of the Westwater Canyon Sandstone are downthrown 20 feet. The pipe has been traced downward into the Recapture Member and upward into the Brushy Basin Member by correlation of drill hole logs. The Dakota Sandstone is not displaced downward in surface drill holes penetrating the pipe, thus the structure is believed to be pre-Dakota in age. The South pipe is ore-bearing.

The North Cliffside pipe (fig. 3) was penetrated by the mine shaft pilot hole, and the bounding ring fault was later intersected by the shaft and by development drifts in the shaft area. The fault is a sharp reverse fracture which shows no associated shattering and little gouge. Locally, it splits into two subparallel faults. There is no brecciation within the structure. The Westwater Canyon Member is displaced downward 20 feet within the pipe. Based on a tenuous correlation of drill-hole resistivity logs, the bounding fault can be traced into the upper one third of the Brushy Basin Member (fig. 3). No ore or carbonaceous matter has been found in or near the North Cliffside pipe.

The Cliffside pipes apparently formed by collapse of a coherent block into a cavity. The cavity could have formed in the Todilto Limestone, which lies 600 feet below the base of the Westwater Canyon Member.

# MINERALOGY

## CARBONACEOUS MATTER

Uranium in the Cliffside mine is intimately associated with black carbonaceous matter, which Granger et al. (1961, p. 1195) classify into three main types, based on mode of occurrence. The first type coats grains and fills interstices in the sandstone and is most common in the Cliffside deposit and in the other mines in the area. The second type fills fractures in the sandstone, both in the black ore and in rare, brown "leached" ore, although it is more noticeable in the brown ore because of the color contrast. The third type replaces wood and bone fragments, which are extremely rare in the Cliffside mine.

## URANIUM

The principal uranium mineral is assumed to be coffinite, which occurs in total association with carbonaceous matter in the Cliffside mine.

A yellow, secondary uranium vanadate(?) occurs in a mottled gray and red sandstone near the fault bounding the southern sedimentary pipe. The mineral is extremely fine-grained; individual crystals are indistinguishable even under high magnification. This is the only observed occurrence of premine oxidized ore in the Cliffside deposit and is noteworthy in that it occurs i000 feet below the present water table.

Efflorescent, secondary yellow uranium minerals are commonly found coating the walls of the older, dry mine workings. These minerals are extremely fine-grained and have not been identified. They are assumed to be soluble uranium sulfates and/or carbonates deposited by evaporation.

## VANADIUM

A 6000-ton sample of the Southwest ore body was obtained by combining the pulps from several mill shipments. This sample includes ore from all parts of the ore body and is believed to be representative. The vanadium oxide content is 0.227 percent, compared with a uranium oxide content of 0.52 percent. The $V_2O_5$: $U_3O_8$ ratio is 0.437, approximately the same as the ratio at the Ann Lee mine.

To determine the distribution of vanadium, nine samples were taken in thin, stratigraphically controlled ore and 18 were taken in and near fractures in thick, structurally controlled ore. The $V_2O_5$: $U_3O_8$ ratio ranges from 0.1 to 1.6. No relationship between vanadium content, or $V_2O_5$: $U_3O_8$ ratio, and type of ore was established by this limited study.

The principal vanadium mineral is presumed to be montroseite or paramontroseite. No postmine vanadium minerals have been recognized.

## SELENIUM

A metallic gray mineral occurs in red or greenish gray mud-stone galls and lenses within the ore. The mineral has two distinct modes of occurrence—as acicular crystals, up to 3 mm in length, which are randomly scattered through the mud-stone, and as striated, flexible blades, up to 2 or 3 mm square, which coat minute curved fracture surfaces in the mudstone. The bladed form resembles small pieces of tinfoil. The stannous chloride test for selenium (Short, 1940, p. 204) is positive, and the mineral is believed to be native selenium. Ralph Austin (written communication) has identified the bladed form as native selenium. The 6000-ton composite sample assayed 0.029 percent selenium, more than five times higher than the average of the ore at the Ann Lee and Sandstone mines. This high assay suggests the presence of red native selenium and/or ferroselite ($FeS_2$); however, neither has been recognized in the ore. If red native selenium is present, as an oxidation product of ferroselite, it would be difficult to identify in red sandstone and mudstone. A pyrite sample is being collected to determine how much, if any, selenium has substituted for sulfur in the pyrite lattice.

## MOLYBDENUM

Halos, pods, and lenses of dark gray to black uranium-deficient sandstone are associated with uranium ore throughout the Ambrosia Lake area. Although this black sandstone superficially resembles ore, it rarely contains more than a few hundredths of one percent $U_3O_8$. It has long been assumed that this material is carbon-impregnated sandstone which was not mineralized. However, recent sampling by Elmer Santos (oral and written communication) has demonstrated that this uranium-deficient sandstone does not contain appreciable amounts of organic carbon. The black color may be due to the presence of jordisite (amorphous molybdenum sulfide) or in some instances, notably in mines above the water table, to a vanadium mineral, probably paramontroseite.

Two samples of this uranium-deficient sandstone in the Cliffside mine were assayed for vanadium oxide and molybdenum. The first sample, a medium gray, fine-grained, well-indurated sandstone, contains 0.153 percent Mo and 0.101 percent $V_2O_5$. The second, a black, fine-grained, friable sandstone, contains 0.118 percent Mo and 0.026 percent $V_2O_5$. The molybdenum content of both samples is much higher than the average of the ore, which is 0.012 percent Mo (6000-ton sample). It is not known why the black sample contains less Mo and $V_2O_5$ than the gray sample; the black color may be due in part to some other mineral. S. Ralph Austin (written

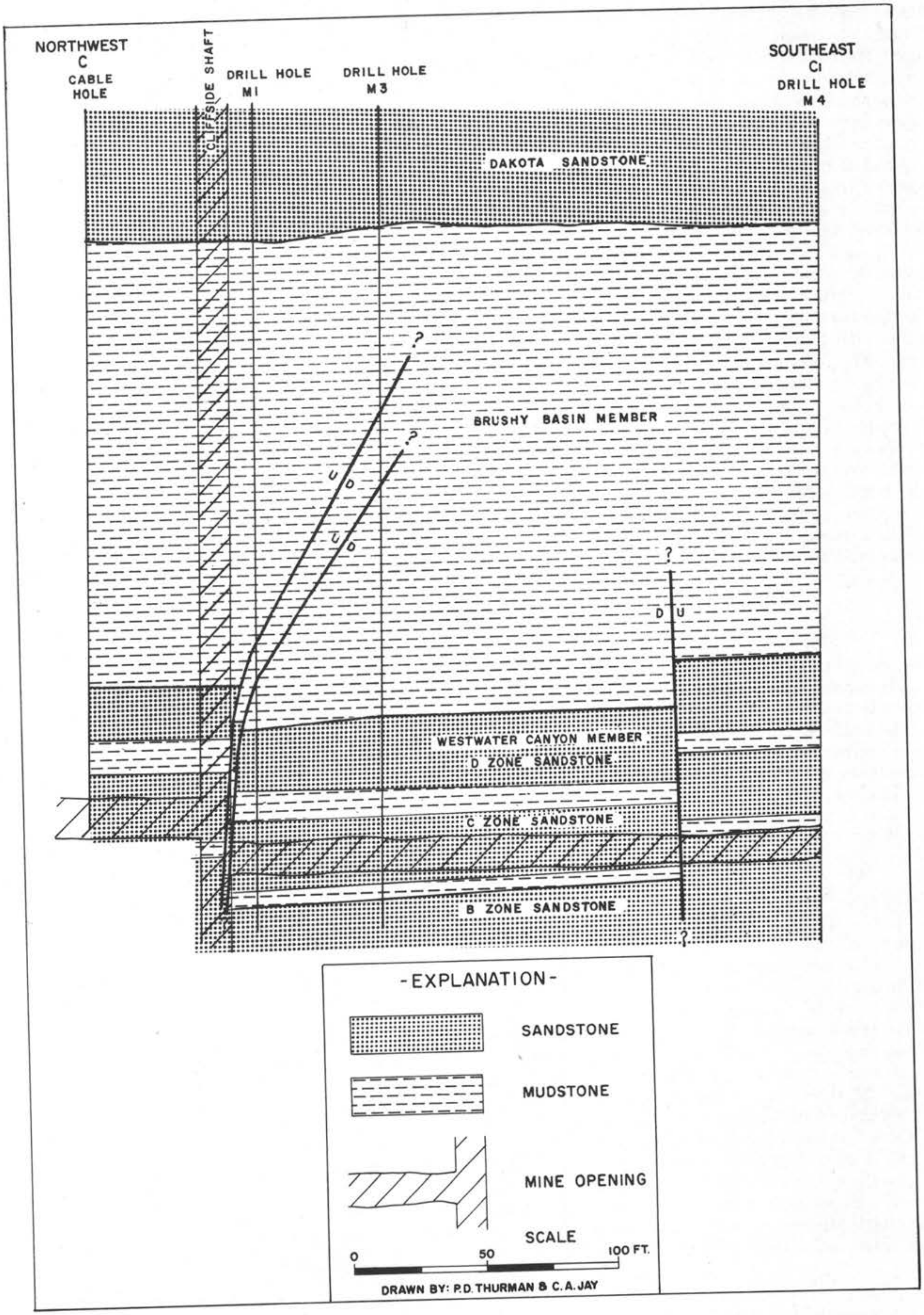


Figure 3

GEOLOGIC SECTION THROUGH NORTH SANDSTONE PIPE, CLIFFSIDE MINE communication) has found that manganese is present in anomalous amounts in some samples of uranium-deficient black sandstone collected in the Ann Lee mine. He suggests the manganese mineral may be psilomelane. Other samples from the Ann Lee mine *(Squyres,* this memoir) contain anomalous amounts of selenium.

Uranium-deficient black sandstone occurs in two distinct modes in the Ambrosia Lake area—as lenticular pods with sharp boundaries and as irregular masses which generally terminate in featherlike projections along bedding planes. An unusual form, resembling the featherlike mode, occurs in one place in the Cliffside mine. Thin bands of the black material, separated by gray waste, transect the bedding in a semicircular pattern, resembling liesegang rings (fig. 4). This phenomenon has not been observed elsewhere in the mine.

Uranium-deficient black sandstone is very abundant in many mines in the Ambrosia Lake area. At the Ann Lee mine, for example, an estimated ten percent of all black sandstone is barren, and at the Sandstone mine the percentage is comparable. Uranium-deficient black sandstone is rare at the Cliffside mine, constituting about one percent of the total black sandstone. The blue molybdenum hydroxide ilsemannite, the oxidation product of jordisite, is apparently very rare; it has been found in only one place in the mine. The molybdenum content of the 6000-ton sample is 0.012 percent. In the Sandstone and Ann Lee mines, where uranium-deficient black sandstone is much more abundant, the molybdenum content is twice as high-0.025 and 0.020 percent, respectively.

## HEAVY MINERALS

Pyrite is the only accessory heavy mineral identified. It occurs sparsely as clusters of minute crystals on sand grains and in mudstone. The scarcity of pyrite and the total absence of crystals larger than 0.2 mm is, we believe, unique in the district. Most of the pyrite is cubic; however, the octahedral form is not uncommon.

## CALCITE

Calcite is a common cementing material in sandstone of the Westwater Canyon Member. While distribution of calcite within individual sandstone beds is irregular, the lower part is generally richer in calcite, and the basal one foot is commonly greatly enriched and very hard. This "hard member" may or may not be ore-bearing. The ore, in general, has a slight preference for calcitic zones within the sandstone. These zones may have been more permeable to uranium-bearing solutions, or the calcite may have acted as a hindrance to later leaching. The age of original emplacement of the calcite is not known; there has undoubtedly been some later redistribution.

Figure 4

BANDS OF URANIUM-DEFICIENT BLACK SANDSTONE TRANSECTING BEDDING PLANES, CLIFFSIDE MINE

## KAOLINITE

Nests of white kaolinite are conspicuous in gray Westwater Canyon Sandstone. Based on limited observations, the kaolinite is equally noticeable in ore and waste; it apparently is not stained by carbonaceous matter or uranium. The nests have not been observed in red sandstone; it is possible that they are stained by the ferric iron. The kaolinite nests commonly enclose several detrital grains. According to Austin (1960, p. 1) they "do not represent feldspar grains altered in situ. Rather, silicon and aluminum from dissolved feldspar were transported at least short distances and deposited as kaolinite."

## ORE DEPOSITS

### DESCRIPTION

The Cliffside deposit lies on the eastern flank of the sag along the San Mateo fault. The deposit consists of two ore bodies: an irregular, roughly circular mass, herein named the *Southwest ore body* and a long, narrow pod extending southeastward almost to the south quarter corner, herein named the *Southeast Extension ore body* (fig. ).

The Southwest ore body consists of a thick central core of ore from which numerous thinner pods, lenses, and tabular bodies of ore project outward at various elevations. The central core lies approximately 700 feet southeast of the shaft. It contains ore averaging 35 to 4o feet in thickness in the combined $B_1$ and C zones. The core is irregularly rectangular in plan, about 30o feet long and 150 feet wide. The long dimension is parallel to the San Mateo fault.

North and west of the central core, the ore occurs as thin, elongated pods and lenses within the $B_1$ and C zones. They range from io to 500 feet in length and from 5 to 7o feet in width and trend east to southeast. The ore ranges from

to 15 feet in thickness and averages about 5 feet. A narrow extension of C zone ore fringes the eastern side of the central core. No other deposits have been found to the east, except for one elongated pod of mineralization in the D zone. Tabular ore bodies in the $B_1$ and C zones extend southward from the central core. Most of these bodies are roughly equidimensional in plan and occur in various sizes up to 30o feet in the longest dimension. They range from 5 to 15 feet in thickness and average about 8 feet.

The South sandstone pipe lies at the southern end of the tabular ore bodies. Ore occurs in the $B_1$ and C zones within and adjacent to the pipe; however, the ore within the structure is much thicker and of higher grade than correlative ore outside it, and the throw of correlative ore does not usually match the stratigraphic throw of 20 feet (fig. 2).

The Southeast Extension ore body (fig. ) has not been developed by mine workings. As defined by surface drill holes, it consists of at least three thin elongated pods in the $B_1$ and C ore zones. These pods trend east to southeast. The ore rarely exceeds ten feet in thickness and averages eight feet. The length of the ore body is approximately I loo feet. The width has not been determined.

Almost all the ore in the Cliffside mine is gray or black. The color of the ore is approximately a function of the grade. The only known occurrence of brown ore is in a small, thick pod of badly fractured, high-grade ore in the extreme western end of the mine, nearest the San Mateo fault. This brown ore forms a lateral fringe to black ore. It is closely associated with the fractures, and it is possible that it migrated from its associated carbonaceous matter and was redeposited.

The ore grade of the Cliffside deposit is much higher than the average of the district. Production to date averages about 0.50 percent $U_30_8$. Thin streaks of ore, ranging from a few inches to somewhat more than a foot in thickness, occur on the edges of many pods and lenses. Most of these thin bands of ore are extremely high in uranium; samples between two and five percent $U_30_8$ are not unusual.

The ore is locally associated with red sandstone and mudstone. Red sandstone is common on the periphery of ore pods, and while it is never ore-bearing, it frequently occurs in direct contact with ore. Blebs, galls, and irregular lenses of red mudstone, normally enclosed by a thin shell of grayish green mudstone, are very common on the periphery of ore pods and often are found within the ore pods.

## ORE CONTROLS

The size, shape, and distribution of the ore bodies in the Cliffside deposit are controlled by both structural and sedimentary features. Sedimentary features include intraformational scours and channels and mudstone layers. Throughout the Ambrosia Lake area, ore deposits are found in east-trending belts of channeling within the Westwater Canyon Member. These channel belts were probably zones of highest permeability in the sandstone and served as conduits for the uranium-bearing solutions. The configuration and orientation of the ore pods north and west of the central core, and of the Southeast Extension ore body, suggests that they are contained within sedimentary channels. These ore bodies comprise approximately ten percent of the total ore in the Cliffside deposit.

The function of grain size as an ore control is not fully understood. The channel belts contain a higher proportion of coarse-grained sandstone lenses; thus, the presence of abundant coarse-grained sandstone is a guide to ore. However, in the Cliffside deposit the ore occurs indiscriminately in coarse-and medium-grained lenses within the channel belt. Nearly all the very high-grade ore in the Cliffside mine, whether stratigraphically or structurally controlled, is found in medium-grained sandstone.

Mudstone layers are an important ore control. The mudstone layer between the $B_1$ and C zones has served as a very effective permeability barrier. The mudstone layer is missing in the area of the central core; the C sandstone apparently scoured through it to rest directly on the underlying $B_1$ sandstone. The two ore zones are thus joined to form a combined zone of much greater than average thickness.

Structural features, including Tertiary joints and pre-Dakota faults, appear to be the major ore control. Ore layers commonly change thickness across joints or terminate against them (fig. 5). The central core of the Southwest ore body is a "stack" of ore concentrated within a zone of northeast striking joints. The ore in the South pipe is obviously controlled by the bounding pre-Dakota fault, since the ore changes thickness across the fault and is not displaced the same amount as the sedimentary units.

## SUMMARY AND CONCLUSIONS

### AGE OF THE ORE

Unoxidized sandstone ore of the Ambrosia Lake area has been classified as prefault and postfault in age (Granger et al., p. 1188-1191 ). Prefault ore is displaced by Tertiary faults, associated with carbonaceous matter, dark in color, generally less than 15 feet thick, and occurs in layered deposits which are primarily stratigraphically controlled. Most prefault ore pods are elongated in an east-southeasterly direction. Postfault ore is later than the Tertiary faulting and is structurally as well as stratigraphically controlled, often forming "stacked" deposits considerably greater than 15 feet thick.

We recognize two types of unoxidized postfault ore in the Ambrosia Lake area. One type, not recognized by Granger et al., is associated with abundant carbonaceous matter and is black. The vanadium content apparently is no higher than in prefault ore. A second type of postfault ore, described by Granger et al. (p. 1188), contains very little carbonaceous matter, is purplish brown, and contains a relatively high proportion of vanadium. This type is most common near or above the water table. The carbonaceous matter and uranium apparently migrated together to form the first type, whereas the uranium migrated separately to form the second type. The second type may represent a later stage of redistribution, after the carbonaceous matter had become nearly insoluble. The carbon-rich postfault ore is generally redistributed along northeast-striking fracture zones. The carbon-deficient type, where seen elsewhere in the district, is controlled by north-striking fracture zones (Rapaport, this memoir). Virtually all the Cliffside redistributed ore is of the carbon-rich type. The only carbon-deficient redistributed ore known is the brown ore fringing the pod in the extreme western end of the mine.

The pods of ore north and west of the central core and the Southeast Extension ore body have all the characteristics of stratigraphically controlled prefault ore. The central core of the Southwest ore body has the typical "stacked" appearance of postfault ore. The mudstone bed between the $B_1$ and C ore zones, which acts as a permeability barrier in other parts of the ore body, is missing, and the ore is stacked up to 5o feet thick along a zone of northeast-trending joints. The thinner, tabular ore bodies south of the central core have the uniform bedded appearance of prefault ore; however, most of the bodies trend roughly northeast, suggesting that considerable structurally controlled redistribution has occurred.

We conclude that the Cliffside deposit was a stratigraphically controlled prefault ore body, the great bulk of which has been redistributed along northeast-striking joints. The interruption of the South Ambrosia trend by essentially barren ground adjacent to the San Mateo fault is interpreted as the result of leaching and removal of prefault uranium deposits by oxidizing solutions introduced from the fault. Some of the dissolved uranium and carbonaceous matter may have been reprecipitated in the Cliffside deposit, explaining the unusually high grade of the ore. The typical prefault ore pods are as high in grade as the "stacked" ore, suggesting that both types of ore were enriched. In the stratigraphically controlled

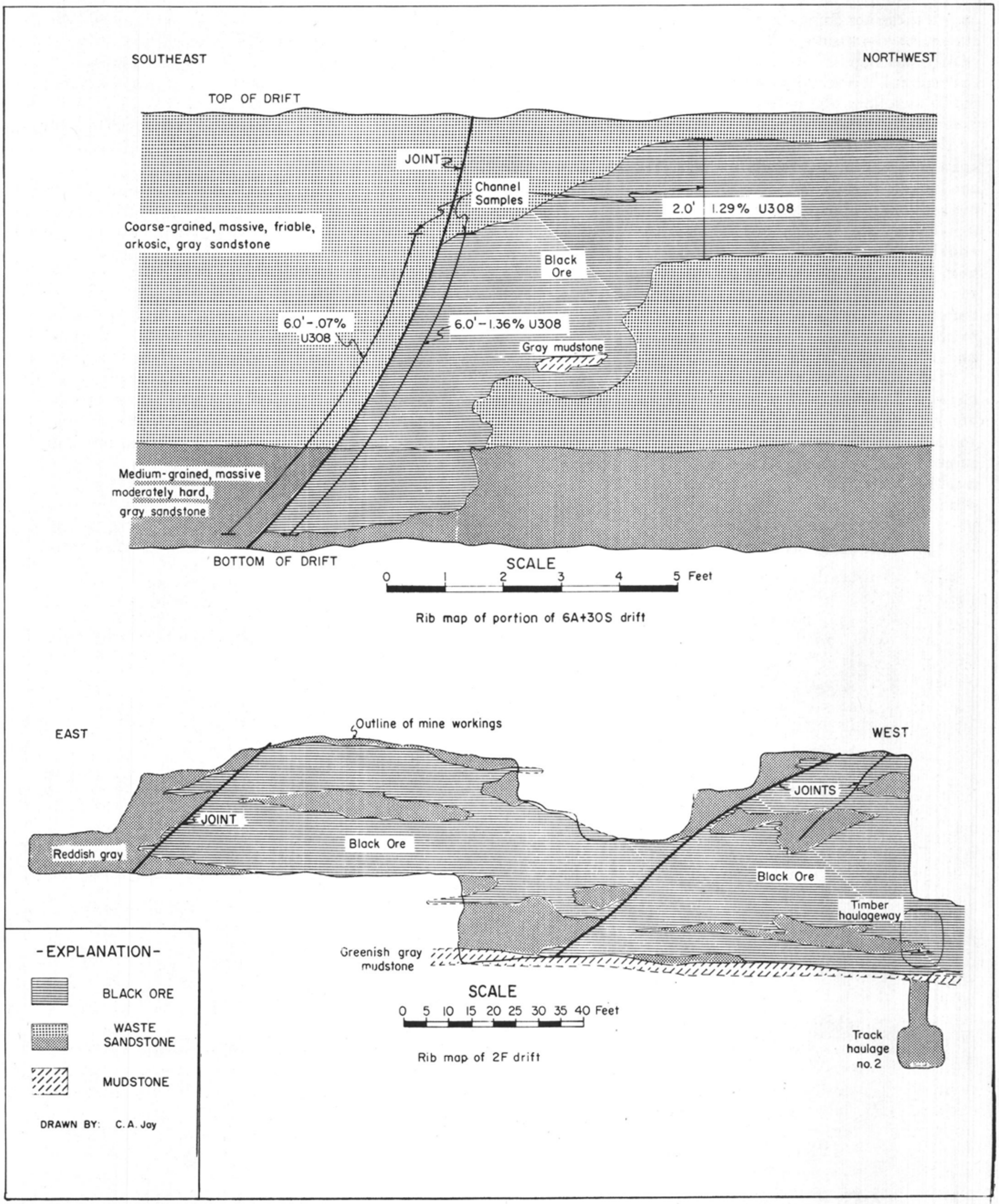


Figure 5

STRUCTURAL CONTROL OF ORE, CLIFFSIDE MINE ore pods, the enriching solutions probably followed the same channels as did the original solutions and did not significantly change the shape of the ore body. The highest grade ore in the deposit lies north and west of the central core, nearest the San Mateo fault; the lowest grade ore lies in the Southeast Extension ore body, farthest from the San Mateo fault.

The ore occurrence in the pre-Dakota pipe (fig. 2) offers some evidence for approximately dating the original mineral emplacement in the area. The ore within the pipe differs markedly in thickness, grade, and stratigraphic position from the ore outside, suggesting that the original mineralization post-dated the formation of the pipe. In other parts of the district, ore is displaced by Tertiary faults (Granger et al., p. 91). The original mineralization therefore occurred earlier than the Tertiary faulting.

The intimate and total association of uranium and black carbonaceous matter in the Cliffside deposit suggests that these materials were deposited by the same solution. According to Vine, Swanson, and Bell (1958, p. 19o), water-soluble humic acids may collect uranium during periods of transport and subsequently be deposited as uranyl humates. The occurrence of ore in one sandstone pipe and the lack of ore in the other suggests that the pipes were neither primary controls of nor conduits for uranium-bearing solutions.

## ALTERATION OF THE SEDIMENTS

It has been stated (Sharpe, 1955, p. 15; Young and Ealy, 1956, p. 6) that the Westwater Canyon Member was probably deposited as an "original" red sediment containing abundant iron oxide and that the favorable pyrite-bearing gray sandstone is derived by diagenetic alteration of the "original" red sandstone (Konigsmark, 1955, p. 5). According to Granger et al. (p. 1193), the existing red sandstone in the district is the result of epigenetic alteration of the pyrite-bearing gray sandstone. If these arguments are correct, parts of the West-water Canyon Member have undergone a cycle from red to gray and back to red again.

Granger et al. (p. 1193) further point out that while "original" red sandstone, if such exists, may be unfavorable for uranium deposits, high-grade ore bodies have been found immediately adjacent to epigenetic red sandstone. This association is common in the Cliffside mine. The red color is thought to be the result of alteration of the gray sandstone by oxidizing ground water introduced from the San Mateo fault. The distribution of this red epigenetic sandstone, which fringes parts of the Cliffside deposit in irregular, discontinuous masses, does not resemble the distribution of the red sandstone in some barren areas of the district, where the entire Westwater Canyon Sandstone is red over dozens of square miles.

At the Cliffside mine, galls and lenses of green-rimmed red mudstone are in places completely surrounded by tens of feet of black high-grade ore. If they are the result of epigenetic alteration of the gray sediments, it seems strange that the oxidizing solutions did not affect the surrounding ore. Furthermore, if the red color is epigenetic, another change to reducing conditions must be postulated to explain the green rims on the mudstone. A simpler explanation is that the red mudstone is relict "original" red sediment which was impervious to reducing solutions. The presence of "original" red mudstone would imply that "original" red sandstone was once present.

## SUMMARY

The Cliffside deposit is unusual in several respects: the equidimensional plan and great thickness of the central core; the high average uranium content; the extreme high grade of thin ore streaks; the scarcity of pyrite; the scarcity of black, uranium-deficient sandstone; the occurrence of sandstone pipes; and the common occurrence of very high-grade unoxidized ore in close association with red sandstone and mudstone.

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# *Geology of the Marquez Mine, Ambrosia Lake Area*

R. J. WEEGE

## INTRODUCTION

In 1955, when exploration activity was in its early stages in the Ambrosia Lake area, Calumet and Hecla acquired the property on which the Marquez mine was eventually discovered. As the ore body did not outcrop at any point, there were no anomalies to guide exploration. The decision to prospect in this area was made on a projection of the Poison Canyon trend which appeared to extend into the Marquez property in section 23. Several mines were under development along this trend, and it seemed reasonable to assume that another ore body might exist along its projection on the Marquez land.

The first exploration drilling was done on a grid system on about 500-foot centers at right angles to the trend. Ore-grade mineralization was encountered in the twentieth hole. Four of the first 13 holes intersected the ore horizon within a lateral distance of 5o to 175 feet from the ore body and were completely barren. Actual discovery of an ore body as opposed to interesting mineralization was made in the fifty-fourth hole. Delineation of the ore body by drilling followed and an engineering and geological evaluation indicated a favorable outcome. The decision was reached to proceed to develop the mine by an incline in view of the shallow nature of the ore body.

As the initial mine openings were driven, it became apparent that the ore occurred in discontinuous lenses and pods that would be difficult to follow with development drifts. This indicated that the ratio of waste rock to ore would be high and that considerable dilution would be experienced during stoping operations if surface drill-hole information was the only source of control. It was also reasoned that some ore might remain undiscovered, since the ore lenses could completely pinch out before hidden ore was exposed.

It was possible, however, that the ore was controlled by structures that could be projected from underground openings into areas where there was little or no information. If this proved to be the case, these structures could be used to great advantage, not only to disclose unknown ore, but also to guide mining with a minimum of dilution. With these thoughts in mind, the Calumet and Hecla geological department initiated an intensive underground mapping and sampling program. The purpose of this paper is to outline the results of this program and to present the theoretical considerations that appear to justify the conclusions that have been reached.

## GENERAL GEOLOGY

The Marquez mine is about 25 miles north of Grants, New Mexico. Unlike most of the ore in the Ambrosia Lake area, the mineralization at the Marquez mine is found in the Poison Canyon sandstone within a trend that parallels the main belt but occurs three to four miles to the southwest. Most of the ore in the district occurs in the stratigraphically lower Westwater Canyon Sandstone. Both members are of Morrison age.

The Poison Canyon unit has been referred to as a tongue of Westwater Canyon. At the Marquez mine, however, the Poison Canyon sandstone is reasonably continuous and is mapped as a separate unit. It is overlain by one hundred or more feet of Brushy Basin shale and is underlain by about twenty feet of the same shale.

## THE POISON CANYON SANDSTONE

The thickness of the Poison Canyon sandstone ranges from nearly zero to about 7o feet in the vicinity of the Marquez mine. Most of the ore is found where the sandstone exceeds 4o feet in thickness.

On the basis of a change in lithology and the presence of a major intraformational disconformity, the Marquez disconformity, the Poison Canyon is subdivided into two units of nearly equal thickness. The unit above the Marquez disconformity is referred to as the "trashy zone"; and the unit below is designated the "favorable zone." Although a small tonnage of ore is found in the trashy zone, it is not considered a favorable host rock. An estimated 90 percent of the ore occurs in the favorable zone, often just beneath the disconformity (fig. 1 ).

### TRASHY ZONE

Perhaps the most diagnostic feature of the trashy zone is the presence of coalified or silicified wood fragments. This material is referred to as trash and in many areas constitutes between i o and 20 percent of the rock. In other areas, little or no trash is present. In general, however, at least trace amounts are recognized. While these woody fragments have been converted in a large degree to carbon, they are rarely mineralized.

This zone is normally an arkosic sandstone that is loosely cemented and poorly sorted. It frequently contains abundant interstitial clay or silt and often grades into a siltstone or claystone.

The upper limit of the trashy zone is the Brushy Basin shale contact and the lower limit is the Marquez disconformity.

### FAVORABLE ZONE

Where the favorable zone has been exposed from top to bottom, it has averaged about 25 feet thick. It is generally a fine- to medium-grained arkosic sandstone, but it may contain coarse to conglomeratic stringers. Clay galls and lenses are common. It is better sorted and contains much less interstitial silt than the trashy zone. Perhaps the most striking difference between the favorable and trashy zones is the absence of woody fragments in the favorable zone. To the writer's knowledge, woody material has never been observed in the favorable zone. Carbonaceous matter is present, however, but it appears to be a chemical derivative of coalified wood, as it is too finely divided to be considered as woody fragments. This type of carbonaceous matter occurs interstitially and has been referred to by various authors as asphalt, asphaltite, hydrocarbon, carbonaceous matter, and kerogen.

The upper limit of the favorable zone is the Marquez disconformity and the lower limit is marked by the Brushy Basin shale.

## THE MARQUEZ DISCONFORMITY

The Marquez disconformity represents an old erosion surface that appears to transect the entire Poison Canyon sandstone in the area under consideration. It can be traced for long distances and generally cuts the underlying beds at angles between I o and 90 degrees.

Frequently, it is marked by mudstone galls or lenses that pinch in and out along its trace on the drift walls. Pyrite or marcasite may occur within it and occasionally gray native selenium is present.

In addition to the Marquez disconformity, there are many less extensive erosional breaks that occur throughout the Poison Canyon unit. These surfaces generally transect each other and are rarely traceable for more than 25 feet. Only occasionally do they exhibit pronounced lithologic changes and only locally do they exercise any control over the position of the ore.

## ORE CONTROLS AND GUIDES TO ORE

### THE MARQUEZ DISCONFORMITY

Much of the ore occurs either immediately below or within the Marquez disconformity. This is especially true near the flanks and on the higher plateaus that existed before the trashy zone was deposited. Underground, this is marked by a sharp turn upward of the Marquez disconformity. In almost all instances, the trashy zone above the plateau areas carries above normal amounts of coalified wood. There is, therefore, a spatial relationship between the unmineralized woody material in the trashy zone and the ore below the disconformity

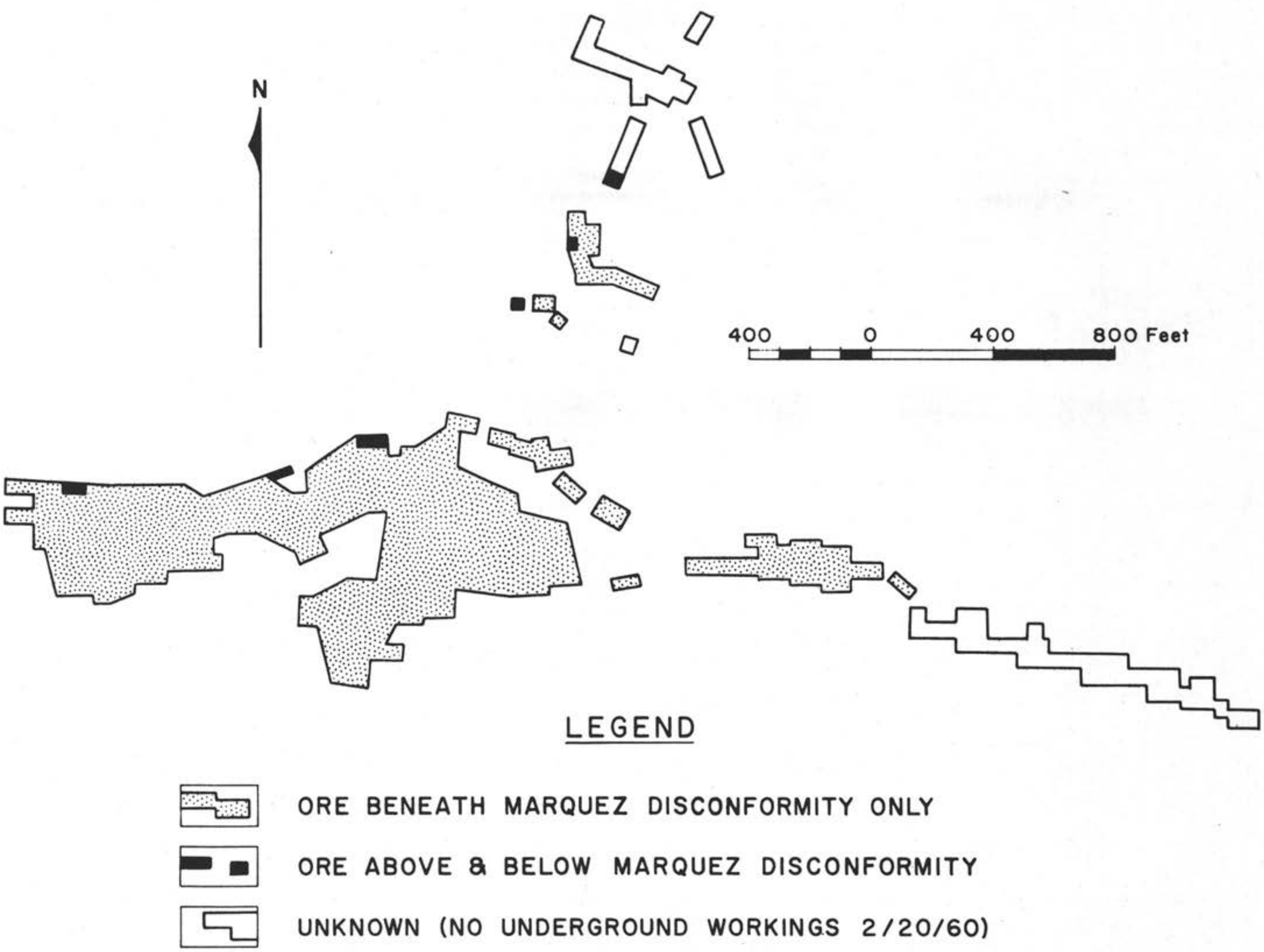


Figure 1

Ore block map of the Marquez mine, showing ore above and below the Marquez disconformity in the favorable zone. This relationship is found throughout the mine and is illustrated by the longitudinal sections in Figures 2 and 3.

## IMPERMEABLE BARRIERS

Relatively impermeable barriers such as mudstone lenses or disconformities that are filled with mudstone appear to locally control the deposition of uranium. High-grade ore is commonly found immediately below the impermeable member and may occur at any stratigraphic position in the favorable zone.

## CARBONACEOUS MATTER

Almost all the ore is associated with carbonaceous material. As pointed out previously, however, the uranium-bearing carbonaceous material differs from the coalified material found in the trashy zone in that it is very finely divided and occurs interstitially in the favorable zone. This distinction is not without exception as an occasional coalified log is mineralized. This, of course, indicates either that the type of carbonaceous matter is important in precipitating or ab sorbing uranium or that the ore-bearing solutions never reached the coalified logs in the trashy zone.

## LITHOLOGY

Most of the ore is found in fine- to medium-grained, fairly well-sorted sandstone. While some coarse-grained rock is ore grade, by far the greater percentage of uranium is found in finer-grained material. This sandstone is usually relatively free of interstitial silt or clay and is locally referred to as a clean sand. This is in contrast to the poorly sorted dirty sand which is characteristic of the trashy zone. A few lenses of clean sand have been found in the trashy zone and several of them have been mineralized.

## THEORETICAL CONSIDERATIONS

In attempting to explain the relationships that have been observed at the Marquez mine, it is of foremost importance to adequately account for the deposition and probable migration of the carbonaceous matter. The close spatial relationships between large amounts of carbonaceous trash above

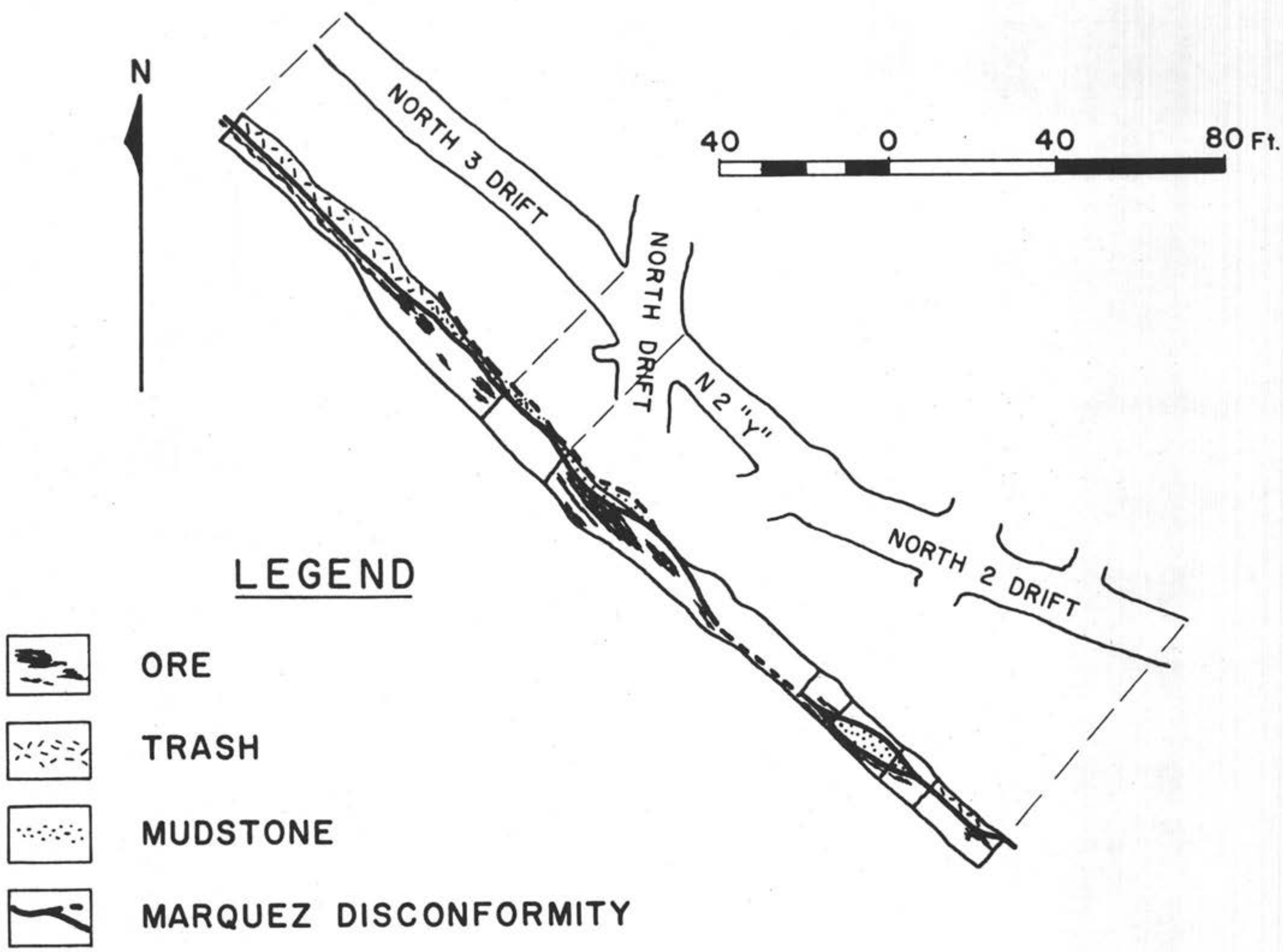


Figure 2

PLAN MAP OF N. # 3, N. 2 "Y", AND N. # 2 DRIFTS WITH GEOLOGIC LONGITUDINAL SECTION OF THE NORTHEAST WALL

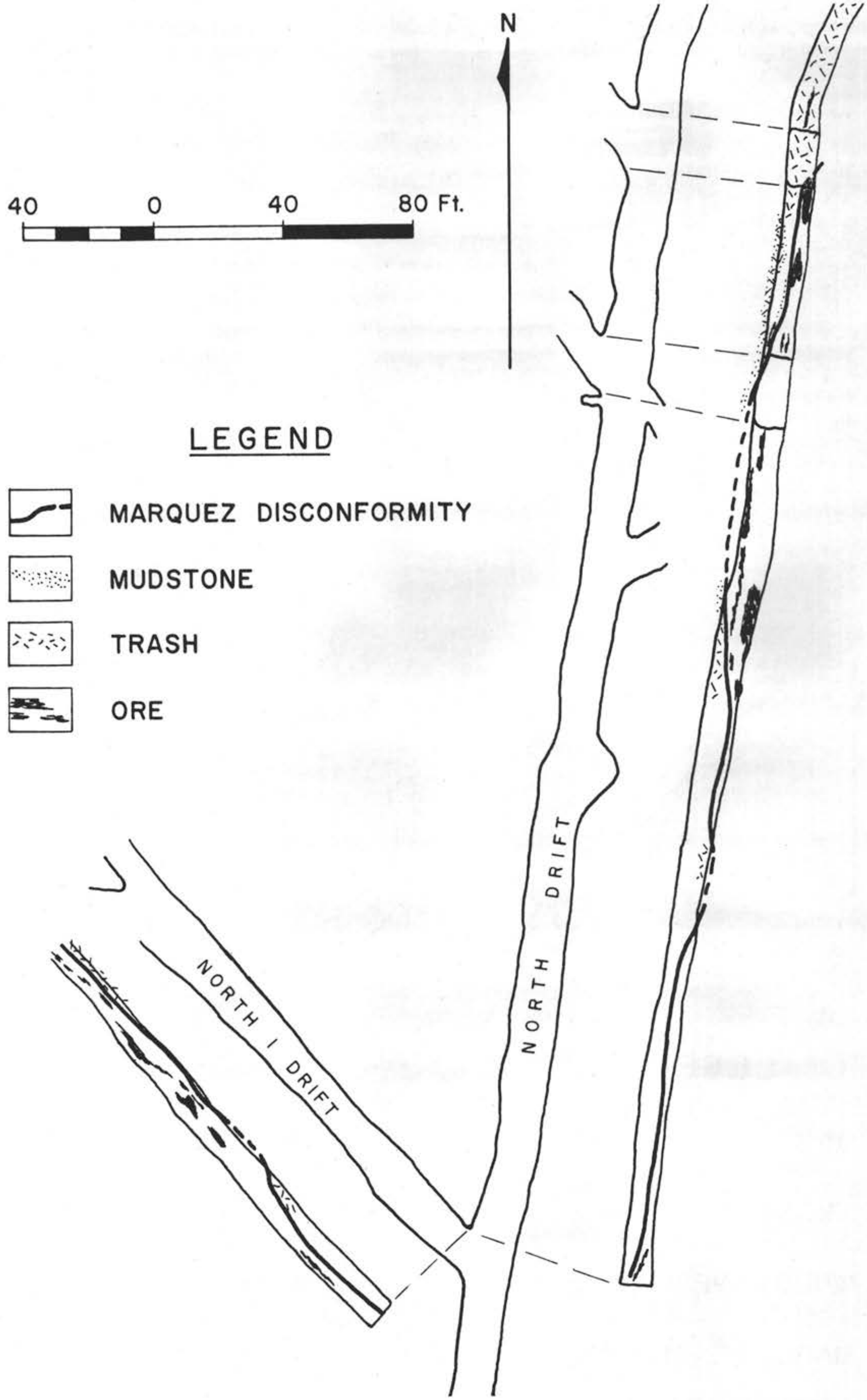


Figure 3

Plan map of north and north no. 1 drifts with geologic sections along the walls the plateau areas and the uranium-bearing interstitial variety below the Marquez disconformity suggests that the interstitial carbon may have been derived from coalified wood.

In a recent paper by Granger et al. (1959), it was suggested that some of the organic material in coalified wood was removed during silicification and diagenetically converted to humic matter soluble in ground waters. These humic-charged ground waters were then moved about under hydrostatic gradients and the carbonaceous matter was precipitated. The evidence that has been accumulated at the Marquez mine tends to support this hypothesis.

During pretrashy zone time when the favorable zone was being eroded, the area now encompassed by the Marquez mine was being cut by a series of streams. After relatively shallow incisions were made in the favorable sandstone, the weather changed and became wetter. The area became the site of violent floods and the poorly sorted, dirty, trashy zone sandstone was rapidly deposited. Logs and other organic debris were thrown onto the banks and plateau areas between the streams. When the trashy zone sand became lithified, the logs and other woody material remained on the flanks and on the plateau areas that are now recognized by the configuration of the Marquez disconformity.

As time went on, the logs were silicified and the released carbon migrated downward short distances and was precipitated in the favorable zone near the plateau areas.

Later, uranium-bearing solutions, which were apparently able to travel freely through the favorable sandstone, encountered the redeposited interstitial carbon and $U_3O_8$ was precipitated. Only limited volumes of the ore-bearing solutions found their way into the trashy zone as very little ore is found in this horizon. The dirty sand of the trashy zone is probably less permeable than the clean sand of the favorable zone, which may have prevented the ore solutions from circulating. In addition, mudstone is often found within or immediately above the Marquez disconformity. Being relatively impermeable, the mudstone may have effectively sealed off the trashy zone from solutions that were traveling either laterally or upward in the favorable zone.

The source of the ore solutions is, of course, speculative. The evidence, however, appears to favor a deep-seated source rather than direct downward migration of surface waters. The thick, overlying Brushy Basin shale would impose a serious barrier to downward migration of meteoric waters. In addition, there is no evidence of appreciable oxidation of the ore, even though most of the mine openings are above the present water table. Furthermore, ore should be found in greater quantities above the Marquez disconformity if the ore solutions came from above. A meteoric source is possible, however, if it is assumed that these solutions were trapped in the favorable zone and migrated laterally under hydrostatic pressure.

## SUMMARY AND CONCLUSIONS

I. The localization of ore at the Marquez mine is controlled by the following sedimentary features:

a. the Marquez disconformity
b. relatively impermeable barriers
c. type of sandstone
d. finely divided intersitial carbonaceous matter

II. The Poison Canyon sandstone is comprised of two units, the trashy zone and the favorable zone. These units differ in lithology and are separated by the Marquez disconformity.

III. An estimated 90 percent of the ore is found in the favorable zone.

IV. There are two types of carbonaceous matter present, coalified wood and the finely divided interstitial variety. Coalified wood is found only in the trashy zone. Interstitial carbonaceous material was probably derived from the coalified wood and may have migrated downward into the favorable zone before the rocks were consolidated.

V. Theoretically, the evidence suggests that the uranium-bearing solutions traveled laterally or upward. Information concerning the source of these solutions is inconclusive.

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# *Uranium Deposits of the Poison Canyon Ore Trend, Grants District*

IRVING RAPAPORT

## INTRODUCTION

Uranium ore deposits of the Poison Canyon area have the aspect of beads of a variety of shapes and sizes scattered along an invisible string (fig. This mineral trend, in its current state of development, is about eight miles long and has been defined by more than one million feet of exploratory drilling. About one million tons of ore have been extracted from open pits, adits, and shafts that have been excavated along the trend, and a similar tonnage awaits exploitation. The Poison Canyon area might have achieved the status of an important district by itself had it not been dwarfed by the subsequent discoveries in the Jackpile and Ambrosia Lake areas.

The initial discovery of sandstone ore in the Grants district was probably made in Poison Canyon in 1951 by a Navajo sheepherder named Paddy Martinez. According to Martinez, sheep by the hundreds had died in a mysterious manner in this valley, and he was drawn to this site by the thought that radiation might have been responsible. An explanation of the death of animals was propounded by Helen Cannon of the U.S. Geological Survey geobotanical branch some years later. Uranium ore in the Poison Canyon area contains appreciable quantities of selenium. The noxious plant, *Astragalus,* grows selectively in the presence of selenium and it was this "rattleweed" that appears to have been the culprit.

## STRATIGRAPHY

The Morrison Formation in the Poison Canyon area consists essentially of two rock types:

*Sandstone.* The coarse-grained elastic rocks are the hosts in this area and are composed of gray, red, and buff, fine-grained to conglomeratic, poorly sorted and poorly cemented sandstones. In approximate order of abundance the constituents are subangular to subrounded clear quartz; flecks and galls of green mudstone; kaolin; subangular to angular pink orthoclase; gray, angular, vitreous plagioclase; chert; granite fragments; and calcite, gypsum, and pyrite crystals. The little cementing material that is present consists of clay and calcite. Fragments of silicified and carbonized wood, gastroliths, and dinosaur bones are quite abundant throughout the Morrison Formation in this are. Scour-and-fill cross-bedding is one of the diagnostic features of the Westwater canyon sandstones. Strata actually consist of a myriad of beveled and dissected channel-fillings which have been superimposed upon each other in infinite variety.

*Mudstone.* The fine-grained elastic rocks of this formation almost never contain ore but appear to have exerted a strong control over ore deposition. The upper mudstones of the Morrison Formation are predominantly pale green. Red, purple, and chocolate-colored strata appear to increase in proportion toward the base of the formation. The clay is bentonitic and is liberally admixed with silt and sand. Stray lenses of gray-green, thin, manly limestone are found within the mudstone layers and occasional cobbles and pebbles of limestone are also visible in the Morrison section.

The anomalous assemblage of fresh angular feldspar, chalky, partially decomposed feldspar, and kaolin grains (completely decomposed feldspar?) is difficult to explain except by pyroclastic action. This analysis appears to be confirmed by the presence of angular fragments of igneous rock, biotite flecks, bentonitic mudstone, and volcanic shards. Volcanic debris appears in greater profusion toward the top of the Morrison Formation and the uppermost (Poison Canyon) sandstone may actually be a tuff that has been incompletely reworked by fluvial action.

The Morrison Formation in this area appears to have been depositedly a network of braided streams and rivers which meandered over a plain of low relief. Sedimentation is believed to have occurred chiefly during times of flood. The coarser elastics were probably deposited in sediment-choked channels contemporaneously with the finer elastics which were carried over the banks in suspension and deposited as relatively pervasive sheets of mud. Channels shifted with each torrent, thereby creating a bewildering series of intertonguing lenses. The mudstone galls and boulders result from the undercutting of banks. The stray limestone strata were probably deposited in ephemeral lakes during periods of quiescence. With this image in mind, the difficulties of correlating Morrison units in the Grants district may be envisioned.

Current flow, as determined by cross-bed directions, log orientations, and heavy mineral lineations, appears to have been in an easterly direction during deposition of upper Morrison sands in this area. This direction is roughly parallel to the local source area, the "Zuni highland," which lay to the south. A longshore current, rather than the expected flow northward directly from the positive area, appears to have distributed the sediment.

The term *Poison Canyon sandstone* was originated by Hilpert to define the uppermost major sandstone unit of the Morrison Formation. The type section was taken near the Poison Canyon mine in sec. 19, T. 13 N., R. 9 W. It is bounded above and below by relatively thick and continuous mudstones. The term has come to have a very useful economic significance and, with extreme care, the lens can be carried with some certainty throughout the Poison Canyon mineral trend. However, this sandstone lens loses its identity to the west and south where it merges imperceptibly with lower Westwater Canyon sandstones which have an identical appearance.

## STRUCTURE

The Zuni uplift has the aspect of a triangular- block that has been uplifted along two deep-seated fault planes and tilted northeasterly. Mesozoic rocks along the northeastern

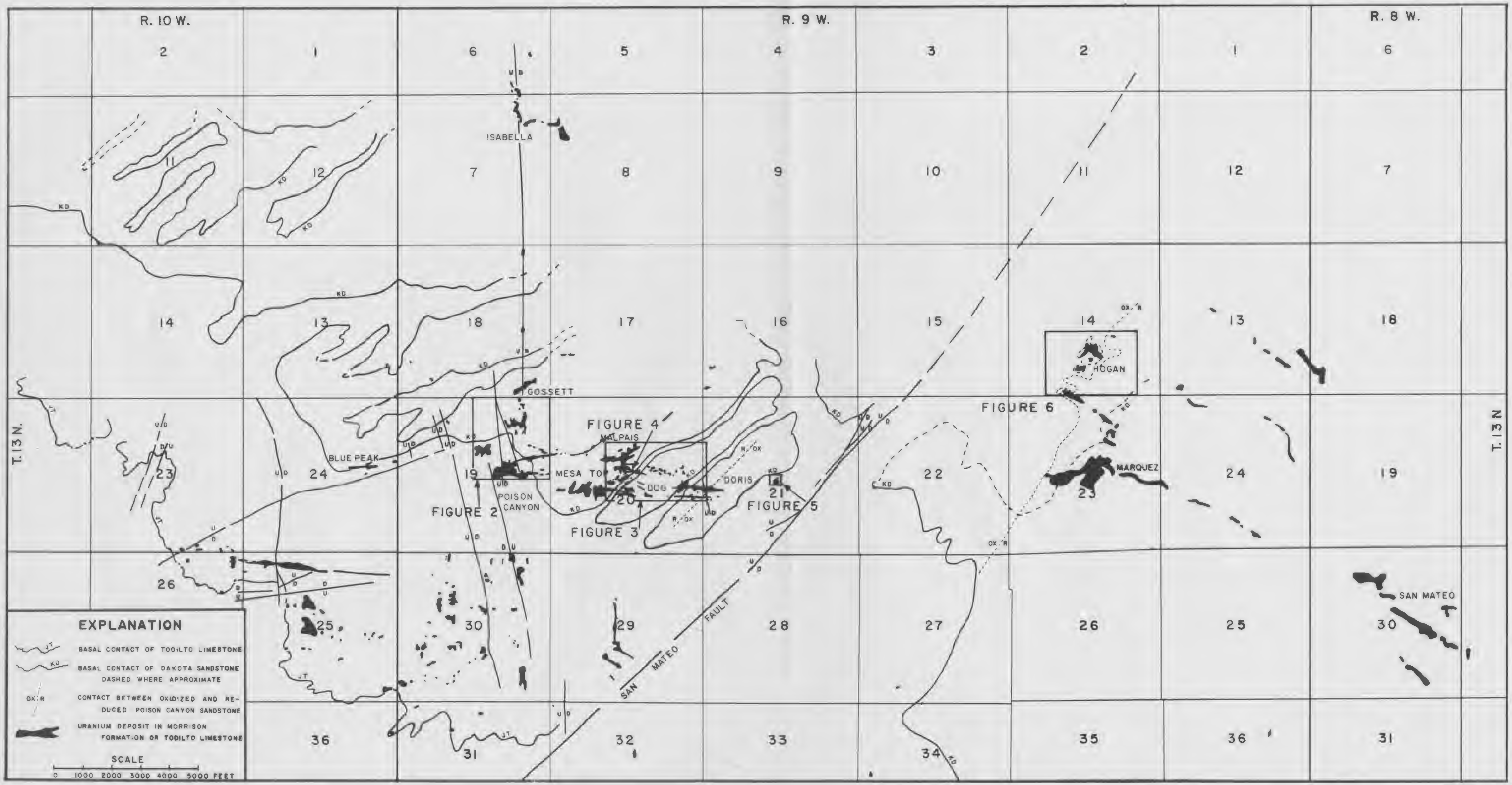


Figure 1

Poison Canyon trend—Grants district, New Mexico flank of the uplift dip gently (2 to 6 degrees) into the San Juan Basin. In contrast, the eastern flank and the Nutria monocline are steep (up to 6o degrees) monoclinal folds which descend abruptly into adjacent synclines. Bucher (personal communication) conceived the idea that the sediments along the monoclines were "draped" over concealed basement faults.

The uranium deposits of the Zuni uplift are localized along the northeastern flank of the structure. Other areas might also have been structurally favorable, but the ore-bearing Jurassic sediments thin to the south as a result of both depositional pinchout and pre-Dakota truncation.

The Poison Canyon area is situated across the northeastern apex of the triangular Zuni uplift. Local structural elements appear to lend themselves readily to classification on the basis of orientation and relative age. The two dominant directions are N. 40°-50° E. and N. 10° W.

N. 40°-50° E.

This is the direction of regional dip throughout most of the Poison Canyon area. Several broad cross folds and transverse normal faults display this orientation.

The San Mateo syncline and the associated San Mateo fault traverse the heart of the Poison Canyon mineral trend and are the most prominent structural features of the area. The valley created along this plane of weakness is filled with about loo feet of alluvium and dune sand; the character of the structure was determined by observation along the flanks and by exploratory drilling. The Dakota Formation on both sides of the syncline is flat-lying and relatively undisturbed. The rocks in the syncline appear to have collapsed. Both blocks of the San Mateo fault, which follows the axis of the syncline, appear to have been depressed; the southeastern block is approximately 25o feet lower than the northwestern block. Several large arroyos on both sides of the San Mateo fault are parallel to it and display strong linearity. The entire Poison Canyon area has been warped into a series of broad, gentle, northeast-striking folds.

The northeast-trending structures are believed to be directly related to the Zuni uplift which achieved maximum development during the Laramide orogeny.

N. 10° W.

The relatively competent, well-cemented Dakota Sandstone yielded to regional stress chiefly by rupture. It is the best available horizon for fracture studies (Gilkey, 1953). The Morrison sandstones are much less competent, form steep, talus-littered slopes, and are difficult to work with on outcrop. Underground, however, the fracture zones are fresh and can be examined in three dimensions. Joints are particularly apparent in stopes that are taking weight; hairline fractures tend to open into fissures along which caving proceeds.

It is estimated that more than 90 percent of the minor faults and shear zones in the western half of the Poison Canyon area trend N. o° W. This structural lineation is also well displayed throughout most of the Zuni uplift. The Bluewater and Zuni faults far to the west have this same orientation. It appears that this joint system was superimposed on the entire region with apparent disregard for local structure. Earlier fracture patterns must have been masked by the N. o° W. joints which developed during a more recent period of movement.

A series of minor normal faults which strike approximately N. 8o° E., at right angles to the dominant N. 10° W. joint direction, have been mapped along the western border of the Poison Canyon area. A vague suggestion of this structural direction can also be seen in indistinct and curving fractures in the Dakota Sandstone.

The N. o° W. structural pattern appears to be superimposed upon the Laramide (?) Zuni uplift and is tentatively assigned a late Tertiary age. Similar relationships have been described by Kelley (1955, p. 45) in the adjacent Lucero and Nacimiento uplifts.

# ORE DEPOSITS

The Poison Canyon mineral trend extends a distance of about eight miles from the Blue Peak mine on the west, where uranium ore occurs at the surface, to the San Mateo mine on the east, where ore lies at a depth of about 1400 feet (fig. ). This zone of ore deposits appears to vary in width from a few hundred feet to as much as a mile. This paper naturally stresses those deposits which **the** writer has operated or studied intensively.

## THE BLUE PEAK MINE

Section 24, T. 13 N., R. Io W.

The Blue Peak mine consists of a series of small discontinuous ore bodies in the Poison Canyon sandstone in the east-central part of the section. Carnotite-type ore was found in 1951 on outcrop in patches of black carbonaceous sandstone along a steep talus-covered slope. Bulldozer cuts were excavated along the rim to expose mineralization and four parallel entries were then driven into the hillside to develop ore.

The following features soon became evident:

1. The ore is intimately associated with the carbonaceous material. Flecks of carnotite, tyuyamunite, autunite, and schroeckingerite are present as accumulations in limonitic sandstone and clustered about fragments of mudstone. However, this brightly colored ore is invariably in close proximity to carbonaceous sandstone ore and appears to result from leaching and redeposition during oxidation.
2. Both carbon and ore seem to be epigenetic. The carbon, which resembles "dried oil," appears to have migrated laterally along local zones of permeability roughly parallel to stratification. Despite a rough conformity to the beds, this organic fluid was not emplaced with the sediments. It transects the cross beds and wanders from one sand lens to another with apparent disreguard for lithology. Careful study fsils to reveal any pronounced affinity of carbon and ore for a particular type of sandstone.
3. A nebulous relationship between ore and solution barriers may be visualized locally. Ore is quite often immediately above or below a mudstone layer, an argillaceous siltstone, or a diastem that contains mudstone fragments.

4. After mining, it seems evident that a definite correlation between the density of fracturing of the host rock and ore existed. The barren and low-grade areas displayed a frequency of about five to ten fractures per-hundred linear feet. Stopes exhibited from 20 to 200 fractures per hundred linear feet. This feature provided one of the few mappable guides to ore in the Blue Peak deposit.

The mineralized zone on this section is about 700 feet long, in an easterly direction, and 5o to 100 feet wide. The Poison Canyon mineral trend is very well defined at its western edge. Intensive drilling through the years behind the outcrop failed to develop additional ore.

The Blue Peak mine is on the western flank of a broad structural depression. The rim curves sharply to the northwest from the vicinity of the mine as it enters the adjacent northeast-plunging anticline (fig. x and Gilkey). A rather abrupt change in the character of the Poison Canyon sandstone, from light gray or white, to a predominantly red or buff color, can be noted concurrent with the structural rise. The upwarped area to the west appears to be devoid of ore. Uranium mineralization is next encountered about three miles to the west, on the eastern flank of the next structural depression, near a fault of about 15o feet displacement. The fault itself is not mineralized, but ore was mined from a fracture zone in a limonitic upper Westwater Canyon Sandstone close to it. A few hundred feet to the west, across the fault, in the downthrown block, uranium mineralization was developed in basal Dakota sandstone. It is interesting to note that both ore bodies are at the same topographic level. The case for redistribution of uranium along a postfault water table seems to be quite strong.

The broad transverse fold upon which the Blue Peak deposit is located plunges northeast. A lateral projection of about two miles, directly updip from the mine, into the Todiltc limestone, manifests a provoking similarity. Despite the absence of a visible lithologic change in the Todilto, virtually no ore is found to the west of this projected line. The same barren three-mile gap is apparent. No significant ore deposit in the Todilto is encountered until the next downwarped area, the Haystack syncline, is reached. Despite a lateral separation of about two miles and a stratigraphic separation of approximately 800 feet, the localization of ore in the same structural depressions is repeated in both ore horizons. It is possible that uranium deposits that once existed in the anticline were removed by the flow of ground water into the adjacent structural depressions.

Detailed mine mapping of the Blue Peak ore deposits aided greatly in the analysis of ore deposition but failed to provide any guides that could be applied in the search for ore. Carbon, minor fracture zones, and solution barriers are almost as restricted as the uranium deposits themselves. Studies of the regional framework of sedimentation and the larger structural elements have proved to be far more useful in devising guides to ore.

## THE POISON CANYON MINE

Section 19, T. 13N., R. 9 W.

The Poison Canyon mine is in a broad re-entrant that was formed by erosion of the Dakota caprock along a series of north-trending shear zones. The valley is buried by alluvium and only a few erosional remnants of Poison Canyon sandstone are visible at the surface. Drilling depths through the Poison Canyon sandstone are under 5o feet throughout much of the mineralized area, and it was economically feasible to delineate ore by percussion and rotary drilling on 2o-foot centers. The bulk of the ore was removed by open-pit methods.

The main Poison Canyon ore body is about half a mile due east of the Blue Peak mine and also shows a strong easterly lineation. The two deposits would probably exhibit greater continuity if the host rock between the mines had not been largely removed by erosion.

The lithology and mineralogy at the Poison Canyon mine is much like that at the Blue Peak mine. Among the specific features of interest observed in the Poison Canyon mine are the following:

I. The southern boundary of the Poison Canyon mineral trend is not obscured by erosion at the Poison Canyon mine as it is at the Blue Peak mine. The southern, updip, margin of the southernmost ore body exhibits a knifelike economic cutoff that strikes east for 1900 feet (fig. 2). There is virtually no dispersion of uranium updip from this, the southern limit of the mineral trend. In contrast, the northern, down-dip limit of the mineral trend is vaguely transitional into barren ground. Erratic, discontinuous patches of ore have been developed for half a mile to the north.

2. A series of minor, north-striking, normal faults has been mapped in the Poison Canyon mine. At first glance, they seem to be postore; uranium mineralization is apparently offset. However, closer inspection of the form of the ore deposits presents conflicting evidence. The largest ore deposit on this property is along the southern margin of the mineral trend. The ore body has a width of 450 feet in the shear zone and pinches to a width of ro to 5o feet in the relatively undisturbed area to the east. It is also interesting to note that the increase in width is achieved in a downdip direction. The updip boundary remains quite straight. Although the lineation of the deposit is to the east, many individual stope walls are precisely parallel to the N. o° W. fracture pattern (fig. 2).

It is my opinion that uranium was initially deposited in the more permeable east-trending sand channels prior to Tertiary deformation. Uranium subsequently migrated downdip, along shear zones formed during Tertiary disturbance, and reconcentrated in new structural and stratigraphic loci.

3. The ore bodies downdip from the major east-trending "primary" deposits have a radically different character that tends to substantiate the theory outlined above.

a. The "redistributed" deposits of the Poison Canyon mine have "amoebalike" forms that fail to show the strong easterly lineation so prominent to the south.

b. The arms of the "amoeba" tend to be aligned in a northerly direction parallel to the post-Dakota joint pattern.

c. Many of these satellitic deposits are relatively deficient in carbon.

d. A "stacking" of bands of ore vertically along structural elements is often shown in the distributed deposits. Where the layers of ore coalesce, thicknesses of up to 4o feet are encountered. The linear primary ore seldom attains a thickness of more than 12 feet.

e. Both primary and redistributed ore consist essentially

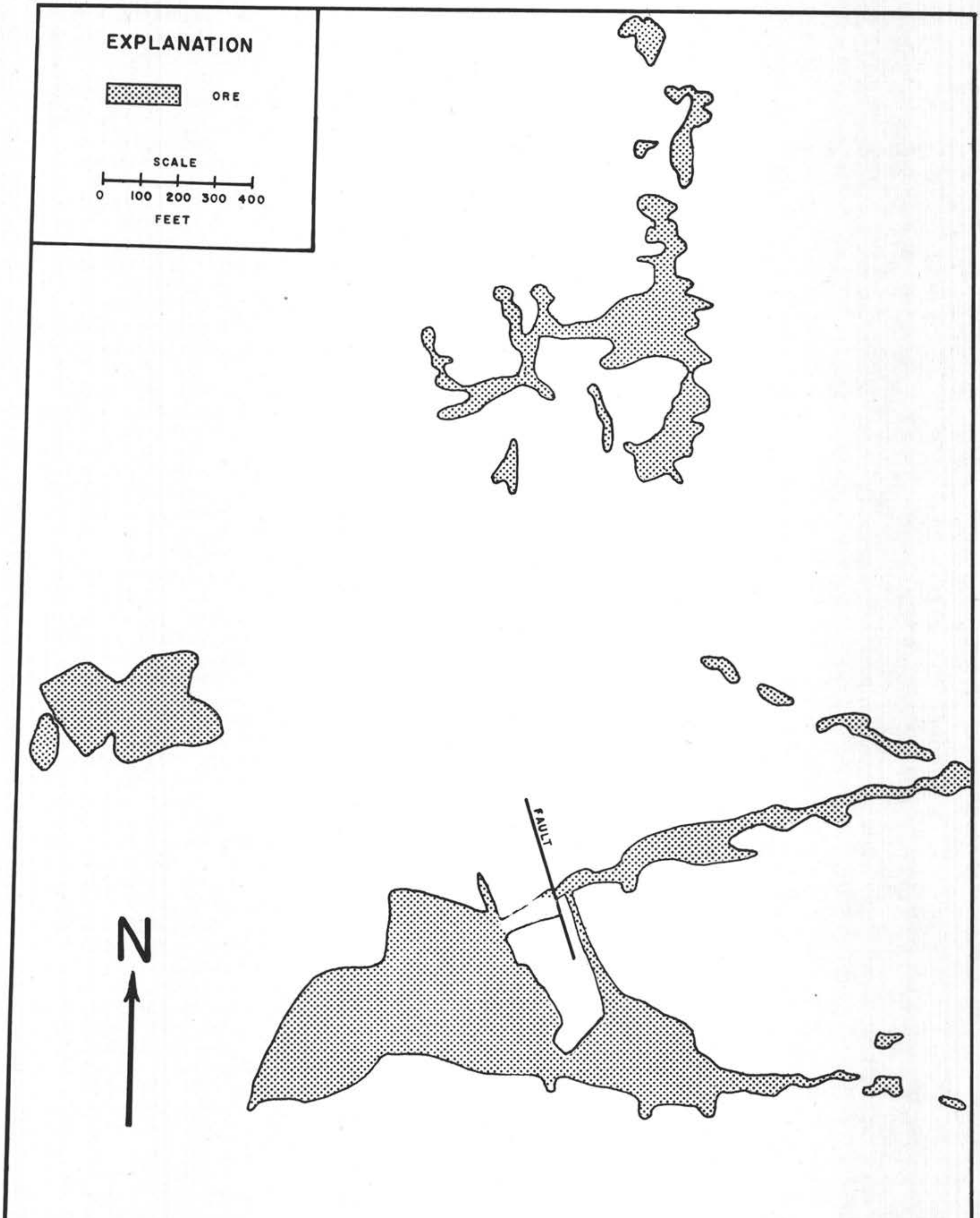


Figure 2

Poison Canyon mine, section 19, T. 13 N., R. 9 W.

of coffinite, a uranium silicate, associated with organic carbon. According to P. Dodd (personal communication), the uranium minerals that have been redistributed in fracture zones are oxidized and the uranium is chiefly in the hexavalent state.

The principal conclusion obtained by the study of the Poison Canyon mine is that ore on that property lends itself to classification into two major types; primary and redistributed, prefault and postfault. Gruner s multiple migration-accretion hypothesis (1956a), which postulates repeated solution, migration, and reprecipitation of uranium throughout the bedded uranium deposits of the western United States, appears to be well substantiated by the features studied at the Poison Canyon mine.

## THE GOSSETT MINE

### Section 18, T.13 N., **R.** 9 W.

The Gossett mine appears to be a redistributed ore body that has subsequently been mobilized by recent meteoric waters. The deposit lies in the southeastern corner of the section, directly north of a chain of similar deposits, in section 19, which extend along the same shear zone from the main Poison Canyon mine. The following features were observed:

1. The ore deposit is along a N. 1o° W. shear zone and the stopes have a similar elongation.
2. Uranium has been leached from a carbonaceous sandstone layer about Io to 20 feet above the basal Brushy Basin mudstone and deposited directly upon it. The fractures between the carbonaceous layer and the basal mudstone are thickly coated with yellow uranium minerals. This is one of the few mines where the fractures themselves have been mined for ore.
3. The ore is in poor radiometric equilibrium. Uranium has been leached preferentially from its associated radium. The carbonaceous layer is highly radioactive but is lacking in uranium. The yellow, oxide-type uranium minerals that have been deposited on the basal mudstone and along fracture planes are deficient in radium; chemical assays exceed radiometric values. The ore-bearing outcrops in Poison Canyon and in the superficial deposits immediately south of the Gossett mine also displayed this differential downward leaching of uranium from its associated radium.
4. The oxidized ores are relatively high in vanadium.

## THE MESA TOP, MALPAIS, BEACON HILL, DAVENPORT, DOG AND FLEA MINES

### Section 20, T. 13 N., R. 9 W.

About fifty individual ore deposits, varying in size from 500 to 50,000 tons, have been developed in section 20. More than 2000 holes, averaging about 16o feet in depth, have been drilled through the Poison Canyon sandstone. Two vertical and four inclined shafts have been sunk to gain access to ore. The continuity of the mineral trend is evidenced by a labyrinth of mine workings which will soon extend completely across the section.

The lithology of the Poison Canyon sandstone and the distribution of uranium deposits within it are similar to those described previously. However, the sheer number of deposits and the intensity of development considerably augment knowledge of the Poison Canyon mineral trend.1

. The thickness of the Poison Canyon sandstone ranges from 35 to 85 feet in the mineralized zone of this section (fig. 3). There is virtually no intertonguing or channeling at the base; increases in thickness are the result of the accumulation of stray sandstone lenses at the top of the unit.

2. Ore is almost entirely confined to the basal forty feet of sandstone. Most of the ore can be relegated to two horizons:

a. The lower ore horizon usually rests directly upon the underlying Brushy Basin mudstone. Ore generally rises abruptly from the mudstone floor at the edges of the ore deposits. The resultant form is analogous to the "rolls" encountered throughout the Uravan mineral belt and may have a similar origin.

The basal Poison Canyon sandstone is thoroughly cemented by calcium carbonate to a depth of six inches to four feet. The zone of cementation does not conform to bedding, is therefore epigenetic, and may be derived by the leaching of the overlying sediment. This "hard rib" often forms a relatively persistent layer of high-grade ore.

The great bulk of ore found in the lower zone is concentrated in remarkably straight, elongate, east-trending channels. Among the examples of the ore deposits of the lower horizon are the S- I ore body of the Dog mine, which is about 25o feet long, ten feet wide, and seven feet thick, and the south Flea deposit, which is approximately 1200 feet long, 25 feet wide, and 9 feet thick. The channels are defined by cross beds within the sandstone and show little, if any, scour into the underlying mudstone. Ore and carbon follow relatively clean foreset beds and seldom extend for more than a few feet into the surrounding flat-bedded sandstone lenses. Ore shoots within the deposits appear to have formed along N. 10° W. fracture zones or in the thicker parts of the sandstone (fig. 4). Most of the basal ore on this property is along the southern margin of the mineral trend.

b. The upper horizon is associated with a persistent, mudstone-littered diastem that lies roughly 20 feet above the base of the Poison Canyon sandstone. The majority of the ore deposits of the upper zone do riot exhibit the marked linearity of the deposits below. The lobate, "amoebalike" form described at Poison Canyon is often displayed. Permeability, as influenced by shear zones, mudstone pinchouts, local diastems, and bedding types, appears to have exerted a strong effect upon ore deposition. Both the ore and host rock at this upper horizon have a more variable character. Most of the ore of the upper horizon is toward the northern edge of the mineral trend.

3. The contrast between the southern and northern boundaries of the mineral trend noted at the Poison Canyon mine is just as pronounced in section 20. The southern margin of the trend is sharp and the sandstone may have an unfavorable, oxidized character one hundred feet south of the ore trend. The northern ore deposits are scattered within a widespread bleached area that extends fat. to the north of the uranium deposits.

4. The two ore horizons coalesce in the central portion

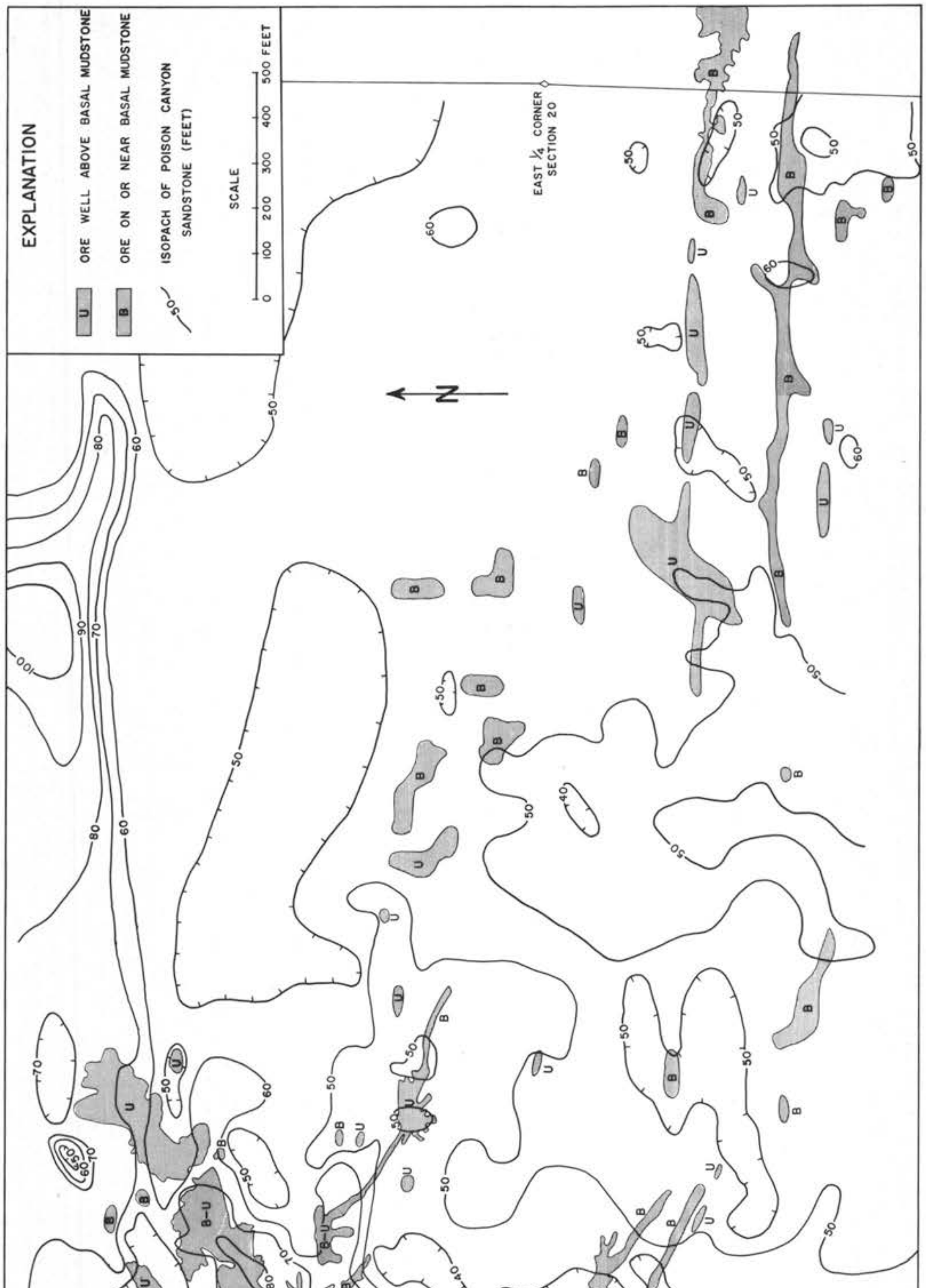


Figure 3

East-central part of section 20, T. 13 N., R. 9 W.

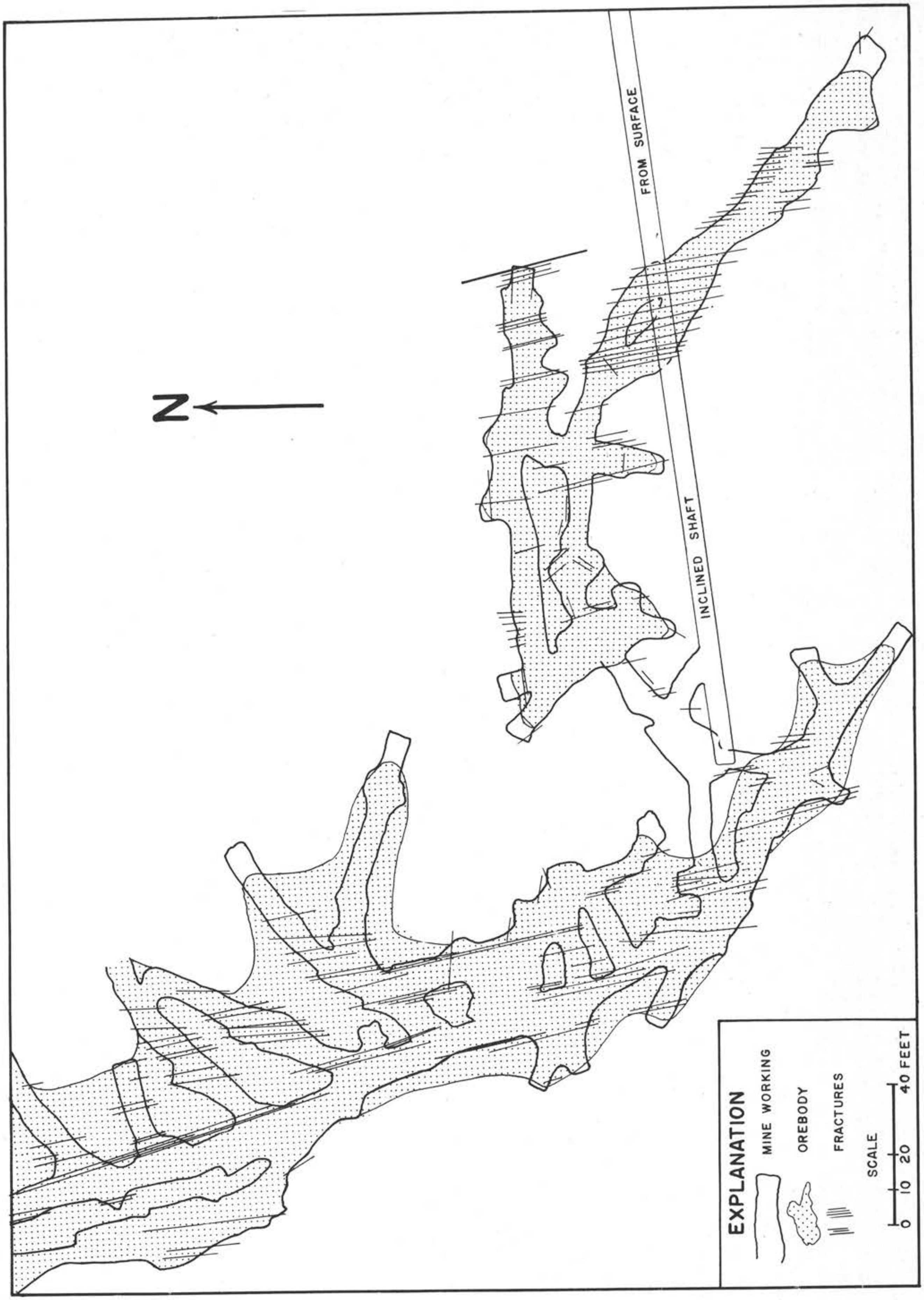


Figure 4
Dog mine, section 20, T. 13 N., R. 9 W.

of the Malpais mine where ore thicknesses of 3o feet have been mined. "Stacking" of ore has been achieved along N. 10° W. fracture zones (fig. 4).

5. The localization of the relatively large Malpais ore body and its adjacent satellitic deposits appears to be related to both a change in channel direction to the northeast and a sandstone build-up. These features, a thickening of the host rock and a change in channel direction, conform to ore controls described throughout the Colorado Plateau. However, similar sand thickenings to the north of the Malpais mine have proved barren, and a series of excellent deposits has been found in a relatively uniform thin sheet of sand to the south and east (fig. 3). Throughout the Poison Canyon mineral trend, the correlation between the thickness of the host rock and uranium mineralization is far from apparent. Gross thickness of the host rock is but one of many factors that controlled the migration and precipitation of ore-bearing fluid within the rock. Had the Poison Canyon sands filled channels eroded in the underlying mudstone and formed sedimentary traps similar to the Shinarump sands of Utah (Evenson and Gray, 1958), a much closer relationship might be expected.

6. Structure contours on the base of the Dakota Sandstone reveal a few minor crenulations which have little apparent correlation with ore. The crenulations do not necessarily describe post-Dakota movement as the top of the Brushy Basin mudstone has been dissected by Cretaceous erosion. No clear relationship between ore and pre-Dakota structure, as mapped on the base of the Poison Canyon sandstone, could be determined.

7. Jordisite, a molybdenum sulfide, and its blue oxidation product, ilsemannite, have been identified in section 20 and throughout most of the Poison Canyon ore trend. These minerals are generally found at the periphery of the deposits; a position that suggests a time of formation later than the associated coffinite and carbon.

## THE DORIS MINE, Section 2 I , T. 13 N., R. 9 W.

My association with this property has been limited to casual underground inspection. The work is that of E. D. McLaughlin, Jr., of the K.S.N. Mining Company, who provided the accompanying illustrations and a stimulating discussion of the salient features of the Doris mine.

1. The Doris West Extension consists of two parallel, east-trending ore deposits, about 200 feet apart, at the western edge of the property. The northern deposit is 10 to 100 feet wide and 700 feet long; the southern deposit is about 15 feet wide and has been mined along trend for approximately 120 feet. All ore appears to be confined to the basal 15 feet of the Poison Canyon sandstone, which has an average thickness of about 5o feet in this area.

2. Redistribution of uranium along a post-Dakota fracture zone can also be observed on this property. A minor N. 15° W. fault offsets ore and carbon but is also the locus of the major ore shoot.

3. Minor pre-Dakota and post-Dakota crenulations do not evidence any apparent control over ore deposition.

4. A sharp contact between oxidized and reduced sandstone was determined by surface drilling and confirmed by mining. All Poison Canyon sandstone in the mine, with the exception of the westernmost 200 feet, appears to have been oxidized. Uranium in the oxidized zone has been mobilized and transported from its original site, whereas the reduced portion of the deposit has remained essentially in place.

Ore within the belt of oxidation consisted of one to two feet of high-grade rock within the calcareous basal "hard rib." This basal ore seemed deficient in carbon and had not yet achieved radiometric equilibrium. A ghost ore body, consisting of carbon and the highly radioactive daughter products of uranium, is about eight feet directly above the enriched ore layer. The ghost ore body assayed about seven feet at 0.07 percent $U_3O_8$, whereas the enriched layer contained an average of approximately 1.5 feet at o.o6 percent $U_3O_8$. The product of these zones is roughly equal to the seven feet of 0.20 percent U308 found in the reduced portion of the deposit; it therefore appears that no appreciable amount of uranium has been carried away.

The contact between oxidized and reduced sandstone could not be related to any topographic or stratigraphic feature. It strikes N. 5o° E., parallel to the adjacent San Mateo syncline and is believed to have been created by the lateral percolation of oxidizing solutions down that structure (fig. I). It is possible that these laterally migrating solutions converted the uranium into a more soluble state without accomplishing any significant transportation. It appears that the oxidized portion of the Doris West Extension was mobilized and carried straight down by recent descending meteoric waters. This form of redistribution, related to recent erosion, is not to be confused with the "redistributed" deposits described previously. The prior types, with the exception of the Gossett mine, are in bleached sandstone, in good radiometric equilibrium, do not exhibit overlying ghost ore bodies, and seem to have formed by lateral migration down dip.

Uranium deposits that may have existed deeper in the San Mateo syncline would have been subjected to more prolonged and more intense oxidation. It is possible that the two-mile gap in mineralization east of the Doris mine resulted from the eradication of ore deposits by late reoxidation.

Oxidation is believed to have occurred near a fluctuating water table. This reaction may have been magnified and accelerated by the contribution of heated gases and fluids to the zone of saturation during the Tertiary. The mineral assemblage of Morrison and Todilto ores, barite, fluorite, pyrite, jordisite, ilsemannite, and native selenium, are suggestive of this phenomenon.

5. The Doris mine is about 1800 feet east and slightly south of the Doris West Extension. Ore appears to have been localized by a conical or cylindrical collapsed pipe within the Poison Canyon sandstone (fig. 5). Although the Dakota Sandstone has been eroded from this area, it is possible to say with some assurance that this is a pre-Dakota structure. Similar pipes in the Morrison formation at the Woodrow mine and at the Cliffside mine (S. Havenstrite, personal communication) are not reflected in the Dakota Sandstone. The host of sandstone pipes in the underlying Summerville Formation is also overlain by undisturbed sediments. The base of the pipe has not been determined, but if the bounding fault does not change dip at depth, the apex of the cone would lie about 500 or 600 feet below the base of the Poison Canyon sandstone in the vicinity of the Summerville Formation.

The origin of such a structure is somewhat problematical.

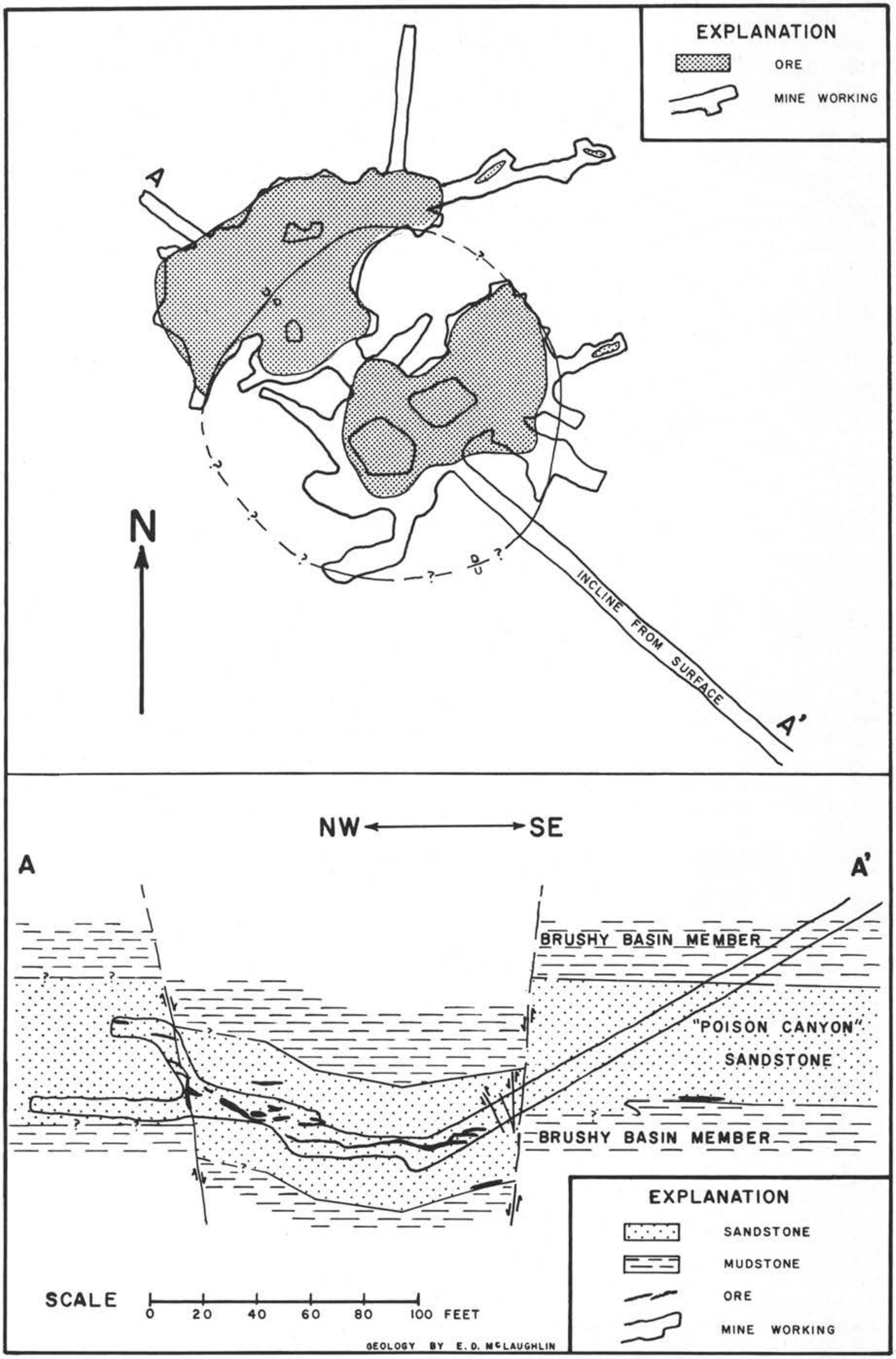


Figure 5

Plan and profile of the Doris mine, section 21, T. 13 N., R. 9 W.

The conical or cylindrical shape and the disturbed bedding suggest the escape of entrapped water under high hydrostatic pressure before complete lithification of the sediment. Subsequent collapse might possibly be related to the removal of soluble material from the underlying rock.

The ring fault is mineralized and ore definitely postdates the structure. The suggested pre-Dakota origin of this structure is not intended to imply a pre-Dakota age for the ore. This deposit has a lobate form which resembles the shape of deposits localized along post-Dakota structures. An ore-bearing solution would not be expected to discriminate between existing structures on the basis of age. This is the only ore body that has been found well within the reoxidized belt and the gouge-coated ring fault may have been the shield that protected this uniquely favored deposit from destruction.

## THE SAN MATEO MINERAL HIATUS

A gap in uranium mineralization extends across the eastern part of section 21, all of section 22, and the western portion of section 23 (fig.1 ). The adjacent properties to the northeast are also barren. The Poison Canyon sandstone has a red or brown oxidized color throughout the mineral hiatus, but with this exception, neither the thickness nor the lithology of the host rock shows any apparent change.

The mineral gap corresponds to the position of the San Mateo syncline and its associated fault. Even the asymmetry of the fold is reflected by the barren zone, which is twice as wide along the southeastern, downthrown block of the fault.

Either uranium was never deposited in the San Mateo syncline or the ore bodies that once existed in this area have been removed. The first possibility seems to be disproved by the fact that many ore deposits transect the smaller Laramide structures and by the fact that the mineral trend projects directly across the San Mateo syncline with little change. The Poison Canyon mineral trend appears to have been formed prior to major tectonic movement. The assumption that ore deposits which once existed in the San Mateo syncline have been flushed downdip by ground water seems to better serve the facts. An almost identical mineral hiatus is exhibited in the Todilto Limestone across the same structure. Shafts sunk in or near this structural depression have encountered large volumes of water under high pressure. Uranium flushed from the San Mateo syncline may or may not have reprecipitated. It is interesting to note that two of the highest grade deposits of the Grants district, the Hogan mine and the Cliff-side mine, are located downdip from the San Mateo mineral hiatus.

The belt of oxidized sandstone parallels the San Mateo syncline and is assumed to have formed subsequent to it. This is not to imply that all oxidation is a recent phenomenon which postdates the initial emplacement of uranium ore. Pale red and buff seem to be the regional colors of all West-water Canyon sandstones and this form of oxidation is believed to have taken place during deposition of the sediment or shortly thereafter. Reduction of iron within the sandstones and the associated color change to gray or white seems to be a widespread pre-Laramide alteration that relates to the percolation of reducing solutions downdip.

A marked decrease in the oxidation potential would be expected where the ore-bearing ground waters first encountered large quantities of carbon. The initial precipitation of uranium is believed to have occurred along this chemical interface. The uranium-depleted solutions, inverted in character from oxidizing to reducing, continued their migration downdip, bleaching the aquifer, but creating few ore deposits. Subsequent Laramide and Tertiary oxidation fronts reoriented and displaced these pre-Laramide deposits downdip to structural and stratigraphic positions that conformed better to the revised structural patterns. This rejuvenation of uranium is a phenomenon that has been described in igneous and sedimentary rocks throughout the world (Davidson, 196o; Gruner, 1956a).

## THE MARQUEZ MINE

### Sections 23 and 24, T. 13 N., R. 9 W.

The Marquez mine is the largest deposit in the Poison Canyon ore trend. The Marquez deposit is described elsewhere in this memoir by Weege of the Calumet and Hecla Mining Company and, therefore, no attempt has been made in this paper to analyze the detailed geology of these interesting and important ore bodies. However, some of the gross features of the Marquez mine which relate to the regional form and distribution of the Poison Canyon ore trend are herein described. The cooperation of Robert W. Kliebenstein and Glen Johnston of Calumet and Hecla is gratefully acknowledged.

I. The principal ore shoot of the Marquez mine is about 2200 feet long and varies in width from 20 feet to almost 1000 feet. A chain of narrow, elongate ore bodies extends eastward from the principal ore shoot for more than a mile. Past this point the ore trend describes a gentle curve to the south. The arcuate form of the ore trend is also implied in three parallel, ore-bearing lineaments to the north (fig. 1).

2. A zone of oxidation, which conforms to the San Mateo syncline, transects the northwestern portion of section 23.

3. South of the ore trend, .bleached Poison Canyon sandstone reverts to a buff limonitic color. The color change is transitional over a wide area. The barren sandstone to the south is generally coarser-grained.

4. According to Kliebenstein and Johnston, the principal ore shoot, which trends northeasterly, appears to be associated with a thickening of the host rock.

5. Linear ore bodies generally lie at the base of the Poison Canyon sandstone. Several deposits, which reveal an "amoeba-like" form and contain ore at a higher horizon, were dis:overed downdip from the major ore shoot.

## THE HOGAN MINE, Section i 4, T. 13 N., R. 9 W.

The Hogan mine is at the northern boundary of the Poison Canyon ore trend. Specific features of the deposits include the following:1

. The Hogan mine is probably one of the best examples of post-Dakota structural control in the Grants district. Ore and carbon are localized along the flank of a sharp anticlinal fold which strikes parallel to the San Mateo fault. The deposit is not merely modified by the structure; it appears to be quite rigidly controlled by it (fig. 6).

2. None of the elongate east-trending ore shoots, so prominent along the southern margin of the mineral trend, could


Figure 6

HOGAN MINE, SECTION 14, T. 13 N., R. 9 W.

be found on this property despite intensive surface and underground exploration. The ore shapes ascribed to redistribution, "amoebalike" in plan and "stacked" in section, dominate completely.

3. A plane of nondeposition and minor erosion within the Poison Canyon sandstone was found about forty feet above the basal mudstone. A gray, fissile, argillaceous silt-stone, which contains an abundance of carbonized wood, lies immediately below this diastem at the Hogan mine.

About 20 to 5o feet of coarse-grained, bright-red sandstone overlies the diastem. This upper sandstone unit is thin or absent at the Marquez mine. The limited value of an isopach map of the gross thickness of the Poison Canyon sandstone as a guide to ore is again demonstrated. The Hogan mine was an excellent ore deposit in a thick (8o feet) sandstone; the Marquez mine is a far better one in a thin (45-foot) sandstone. Virtually all ore in both mines is confined to the basal forty feet of sand. The thickness of the red sandstone lens at the Hogan mine above the diastem appears to have exerted little or no effect upon uranium deposition.

4. Mineralization at the Hogan mine can be roughly classified into three zones:

a. The basal ore zone rests directly upon the lower Brushy Basin mudstone and is associated with the ubiquitous, calcareous "hard rib." The ore at this lowest horizon is about 500 feet long, Io to 8o feet wide, and trends in an arcuate manner from S. 40° E. to S. 7o° E. Structure contours drawn upon the base of ore revealed a remarkable "canoelike" shape. The highest-grade, thickest ore was along the "keel" of the "canoe." When the main haulageway was driven along the axis of the deposit, ore was noted to ascend from the basal mudstone in all directions, like the sides of a canoe, transecting bedding and merging with the higher ore zones. Neither pre-Dakota nor post-Dakota tectonic structure could be related to this peculiar semicylindrical ore form. It is possible that ore-bearing solutions flowed through an imperceptible sedimentary zone of increased permeability that is now masked by carbon, calcite, coffinite, pyrite, jordisite, and secondary structure. The semicylindrical form described by the basal ore would have permitted a maximum volume of solution to pass through a minimal cross-sectional area.

b. The intermediate zone of ore is more widespread and erratic than the basal zone and lacks any marked lineation. This ore horizon is 15 to 25 feet above the basal mudstone and the economic limits of individual stopes appear to have been controlled by local solution barriers and variations in permeability. This horizon is similar in character to the upper zone of ore described for section 20 and is found at about the same stratigraphic position.

c. The uppermost ore zone in the Hogan mine lies directly below the diastem. The fissile, carbonaceous siltstone below the diastem, forms the most persistent layer of ore in the mine but is generally low grade and thin. Truly economic values were only obtained where mineralization extended down from the siltstone into underlying sandstone lenses.

5. The central, thick, high-grade core of the Hogan ore deposit has been thoroughly shattered along closely spaced joints. Ore appears to have migrated abruptly from one horizon to another, creating a series of almost vertical, curving ore forms. All three ore horizons merged locally along the central core and, in some stopes, the complete 4o-foot interval from basal mudstone to the diastem has been mined.

The great majority of fractures and minor faults at the Hogan mine strikes N. 10° W. A northeast-striking fracture system, parallel to the axis of the anticlinal fold, was also observed. Calcite, pyrite, marcasite, and occasional crystals of brown barite have been found as coatings in both fracture systems. The mudstone underlying the host rock has been forced into drag folds which strike parallel to the axis of the anticline. Fractures in the sandstone above the drag folds were intruded by mudstone dikes extending upward from the floor.

6. Ore at the Hogan mine occurs at the interface between red and gray sandstone (fig. 6). The red color of the sandstone is believed to be the result of post-Cretaceous reoxidation.

a. The Hogan oxidized zone transects the Poison Canyon ore trend, but parallels the San Mateo syncline, a post-Dakota structure. In contrast, the oxidized rock along the southern margin of the Poison Canyon ore trend parallels the trend, transects minor post-Dakota structures, and appears to have formed prior to regional deformation.

b. The interface between red and gray sandstone at the Hogan mine is a knife-edge contact. The oxidized-reduced contact along the southern edge of the ore trend is far more transitional.

c. Oxidized rock at the Hogan mine has a bright red color. The barren sandstone south of the mineral trend is generally pale red, buff, or pale yellow.

d. The principal ore body has the aspect of an "inclusion" of bleached sandstone that has been completely enveloped by oxidized rock. The edges of the deposit itself seem to have suffered postore oxidation. Tongues of bright red mudstone and sandstone transect both bedding and ore. The blackness of the rock, a criterion that is employed thoughout the Grants district to gauge ore value, applied poorly at the Hogan mine. The effect of reoxidation was so profound that good grade stockpiles of ore often had a red cast.

It is possible that some uranium at the Hogan mine was removed by late oxidizing solutions. The unusually heavy concentrations of carbon, carbonized wood, and molybdenum may have served to fix the uranium and impede total destruction of the ore deposit.

## CONCLUSIONS

1. The Poison Canyon sandstone was deposited in an aqueous continental environment and is composed of intercalated, feldspathic sandstone and bentonitic mudstone. Volcanic debris comprises a large portion of the sediment. The close association of uranium, throughout the vast area of the Colorado Plateau, with host rocks of this lithologic type and the paucity of hydrothermal effects in most districts strongly imply that uranium was derived from the sediments themselves.

2. Uranuim ore in the Poison Canyon trend has been deposited by laterally migrating ground water.

3. The initial emplacement of ore occurred prior to the Zuni uplift, a structure which is believed to have developed during Laramide time. Many of the ore deposits subsequently suffered mobilization and redistribution. The principal surges in migration probably correlate with spasms of tectonic and volcanic activity. The ore deposits are relegated to four principal categories on the basis of their relationship to structure and carbon:

a. Deposits which exhibit no visible relationship to Laramide or post-Laramide structure are considered to be original. The Poison Canyon ore trend itself, and most of the individual deposits along the southern margin of the trend, transect all post-Dakota structures and are offset by post-Dakota faults. These deposits are elongate and appear to have formed along east-trending linear or arcuate zones of permeability at the base of the sandstone.

The Zuni highland, the closest source area of Jurassic sediment, is the only structure to which the form of the Poison Canyon ore trend can be related. The two are parallel and it is assumed that the regional flow of uranium-bearing ground water was controlled by this dominant preLaramide structural element. The interaction of fresh and saline water has been suggested as a mechanism for the precipitation of uranium (W. Ashwill, personal communication). If such an interface existed before Laramide deformation it, too, would have been parallel to the Zuni highland.

Local structural features and the physical and chemical character of the aquifer probably determined the specific sites of ore deposition. There is an indication that some ore shoots formed in the thicker parts of the host rock. The ore trend itself, howevr, transects these local variations.

The primary deposits of the Poison Canyon ore trend contain an abundance of carbon, are well-defined, and have a fairly uniform thickness that seldom exceeds 12 feet. The deposits generally show remarkable continuity along trend.

Uranium is intimately associated with an organic fluid, which has the appearance of "dried oil" that has been variously called carbon, asphaltite, kerogen, and carbonaceous material.

Uranium is believed to have precipitated initially along a chemical interface formed by the interaction of oxidizing, ore-bearing ground water and concentrations of carbon. The intimate spatial relationship of uranium and carbon throughout the mineral trend, and the integrated nature of ore textures, imply that the two fluids were generated at about the same time. Past the interface, the solutions were depleted in uranium and inverted in character from oxidizing to reducing. Relatively few pre-Laramide ore deposits have been discovered in the pervasive bleached zone which extends downdip from the southern margin of the ore trend. The zone of reduced Poison Canyon sandstone also persists far beyond the redistributed ore bodies which define the northern limit of the ore trend.

b. The second type of deposit displays a relationship to northeast-trending Laramide (?) structures. The scarcity of Tertiary beds in the area precludes a conclusive determination of age, but early and later structures can be distinguished. Ore bodies of this generation are generally aligned in a northeasterly direction, downdip from the primary deposits. A lobate shape, which contrasts sharply with the linear form of the primary deposits, is prevalent. Layers of ore seem to be "stacked" vertically in areas that were structurally or stratigraphically favorable and ore thicknesses of 4o feet have been encountered where ore zones coalesce. Radical variations in the tenor of ore, both laterally and vertically, are common within the deposits and a variety of curving vertical ore forms between ore layers can often be observed. The outer limits of ore are usually well defined and the deposits are generally at a higher stratigraphic position.

The redistributed deposits of this generation are often extremely rich in carbon. It is assumed that the organic material was still fluid during the early Tertiary and that the migration to more favorable structural and stratigraphic loci was motivated by the changing structural pattern. The peregrination of uranium and carbon is believed to have been concurrent during this stage of redistribution.

c. The third type of deposit correlates with a N. 0° W. fracture system that is tentatively assigned a late Tertiary age. The joint pattern that developed during this period of movement appears to have been superimposed on all pre-existing structures. Laramide (?) and pre-Laramide joint systems appear to have been virtually obliterated in this area.

Deposits of this type tend to align along N. 10° W. shear zones or faults which extend north from primary or secondary deposits. They resemble the Laramide (?) redistributed ore bodies in that they are generally lobate, "stacked," thick, and erratic. They also tend to form at higher stratigraphic horizons than the primary deposits. Mineralization is generally pervasive and ore boundaries are ill-defined.

Most of the late Tertiary (?) ore bodies that have been transported an appreciable distance seem to be relatively deficient in carbon. The organic fluid probably had become quite viscous by this time. Uranium seems to have migrated away from the carbon and reprecipitated in limonitic sandstone. These deposits are sufficiently old to have attained radiometric equilibrium.

d. The fourth type of deposit was created by the downward percolation of recent meteoric water. These deposits are distinguished by thin layers of high-grade ore which rest directly upon the basal mudstone and by open fractures which are coated with yellow, oxide-type uranium minerals. Ghost ore bodies composed of carbon and the highly radioactive daughter products of uranium can be found directly above this most recent generation of ore. Insufficient time has elapsed for the ore to achieve radiometric equilibrium.

Many of the ore deposits of the Poison Canyon trend seem to be a composite of two or more of the above types. Ore shoots within essentially primary ore bodies may exhibit reorientation and enrichment along post-Dakota shear zones with a bare minimum of migration. Other deposits appear to have been completely divorced from the parent trend.

4. Two types of red or brown oxidized sandstone can be distinguished. The first type transects post-Dakota structure and parallels the southern margin of the Poison Canyon ore trend. It grades transitionally into the ore-bearing bleached

rock. This is believed to be the original or diagenetic color of the Westwater Canyon Sandstone.

The second type of oxidized sandstone occurs in a belt which parallels the asymmetric San Mateo syncline. This is believed to be a belt of reoxidation which was created by the flow of ground water down the structure subsequent to the formation of the Laramide (?) uranium deposits. The ore deposits that probably existed within this structure prior to reoxidation have been mobilized and dispersed.

5. The mineral assemblage of Morrison and Todilto ores suggests the contribution of hydrothermal fluids and gases to the water table during periods of Tertiary igneous activity. The question of the contribution of additional uranium at these times still seems to defy solution.

6. The molydenum mineral jordisite and its oxidation product, ilsemannite, have been found in quantity at the periphery of Type A and Type B ore bodies. Molydenum mineralization is assumed to be younger than the deposits. The greatest concentration of these minerals was observed at the Malpais and Hogan mines, Type B deposits.

7. Type C and D deposits appear to have higher $V_2O_5$: $U_3O_8$ ratios. The vanadium content of Todilto ores also appears to be a function of oxidation. Granger et al. (1961) stated that vanadium is concentrated in the upper part of Ambrosia Lake deposits. These features imply that much of the vanadium may be the result of supergene enrichment.

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# *Uranium Deposits in the Todilto Limestone of the Grants District*

E. D. MCLAUGHLIN, JR.

## INTRODUCTION

The original discovery of uranium in the Grants district was made in the Todilto Limestone near Haystack Butte. Since that discovery, ore produced from this formation has represented the only important uranium production from limestone in the United States. Subsequent ore discoveries a few miles northward in the Morrison Formation have since dwarfed the importance of Todilto ore to the extent that, at present, this ore represents less than one percent of total district production. At this time, most known ore reserves in the Todilto have been depleted, and exploration for new deposits since 1959 has been relatively slight.

Significant and unique geologic relationships were early recognized in the uranium deposits of the Todilto. The purpose of this paper is to summarize and correlate the findings of earlier investigators in the light of most recent information and to furnish some additional insight into the geology and economics of these deposits.

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## LOCATION

The Todilto Limestone crops out along the northeast-dipping Thoreau homocline in a belt trending generally northwest-southeast across southern McKinley and northern Valencia counties, New Mexico (fig. 1). Uranium occurrences have been reported at scattered localities along these rim outcrops northwestward to near Gallup and southeastward to the southern part of the Laguna Indian Reservation. Important ore production, however, has come only from the part of this outcrop belt bounded to the northwest by sec. 13, T. 13 N., R. II W., and to the southeast by sec. 34, T. 12 N., R. 9 W.

## STRATIGRAPHY

### TODILTO FORMATION

The following description of the Todilto Formation of the San Juan Basin is summarized here from Rapaport, Hadfield, and Olson (1952, p. 23-27) and Gableman (1956, p. 389).

I. The Todilto Formation is of Late Jurassic age and was deposited in an elliptical basin which extended about 300 miles east-west and about loo miles north and south. The location of this basin about matches that of the San Juan Basin along the southwest and west margins.

2. The formation is composed of two members, a lower, thin, extensive limestone member and an upper, more restricted, thick, gypsum member. In the eastern part of the San Juan Basin, the limestone member is generally from five to ten feet thick, and the overlying gypsum member reaches thicknesses of up to 95 feet. In the western part of the basin, generally only the limestone member is present. It varies in thickness from about 25 feet in the Grants district to one foot or less near the southwest strand line of the basin a few miles east of Gallup.

3. The Todilto Limestone commonly contains siltstone partings and is slightly petroliferous. It has been considered lacustrine, principally because of fresh-water fossils found near the western limit, but has also, along with the gypsum unit, been considered marine.

4. The limestone unit has been correlated with the marine Curtis Formation of Utah and with the Pony Express Member of the Wanakah Formation of southwestern Colorado.

5. Known uranium deposits (in other than the Grants district) in the Todilto Limestone occur in the Sanostee, Rio Cebolla, Arroyo del Aqua, and Laguna areas around the west, east, and southeast margins of the San Juan Basin. With the exception of the Laguna deposit, these deposits consist of secondary uranium minerals filling fractures and vugs in the limestone and have not been the source of significant ore production. Uranium has not been found where the formation is gypsiferous, except in the Rio Cebolla area.

Certain similarities exist between the above-mentioned uranium deposits, as described by Gableman, and those of the Grants district. These similarities include the association of uranium with folding and with selective recrystallization of limestone.

## TODILTO FORMATION IN THE GRANTS DISTRICT

The Todilto Formation in the Grants district overlies the Entrada Sandstone and is overlain by the Summerville Formation. The Todilto in this area is a limestone facies up to 3o feet in thickness, with thin and irregular interbeds of siltstone, sandstone, and gypsum. All units apparently contain slight amounts of petroleum and characteristically release a petroliferous odor when struck or fractured—a characteristic apparently unaffected by recrystallization. Throughout most of the district, two zones are recognizable and are known as the platy (lower) zone and the crinkly (middle) zone. Also present throughout much of the district, though locally absent, is a third zone known as the massive (upper) zone (fig. 2). These zones are described below.

*Platy (lower) zone.* The platy zone is usually ten to 15 feet thick and is a light gray to light grayish brown, dense, fine-grained limestone with generally regular bedding ranging from thinly laminated up to six inches. Siltstone and sandstone partings of up to a few inches thickness are common and are most abundant near the base. Two to four near-white, highly gypsiferous beds are sometimes present and are useful on a local basis as marker beds. These beds are usually four to six inches thick.

*Crinkly (middle) zone.* The crinkly zone is generally three to six feet thick and is a light gray to light grayish brown, extensively recrystallized limestone with bedding ranging from very thinly laminated up to a few inches. Bedding is marked by conspicuous crenulations up to sev-

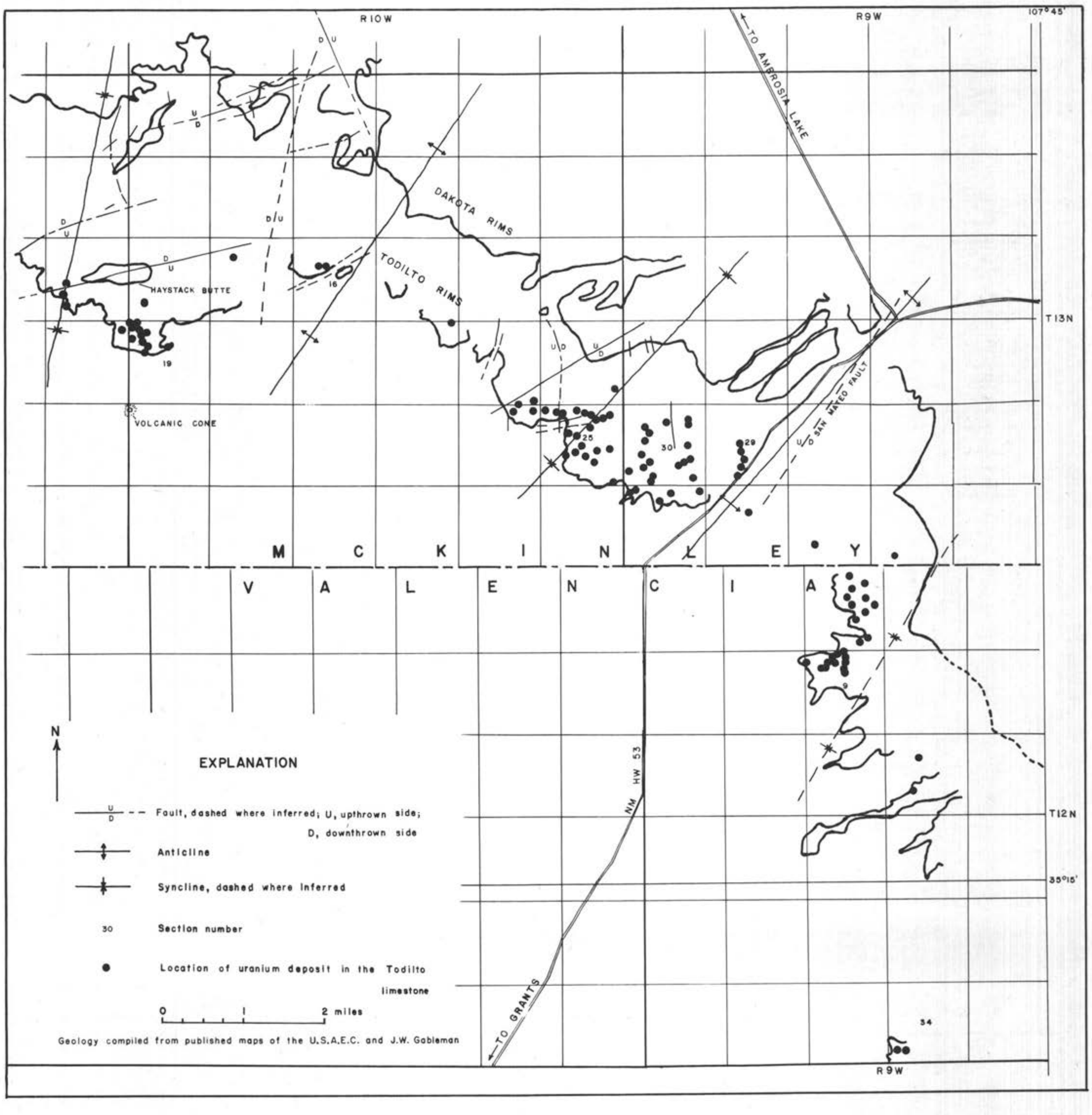


Figure 1

MAP SHOWING DISTRIBUTION OF TODILTO DEPOSITS AND CERTAIN ASSOCIATED FOLDS AND FAULTS

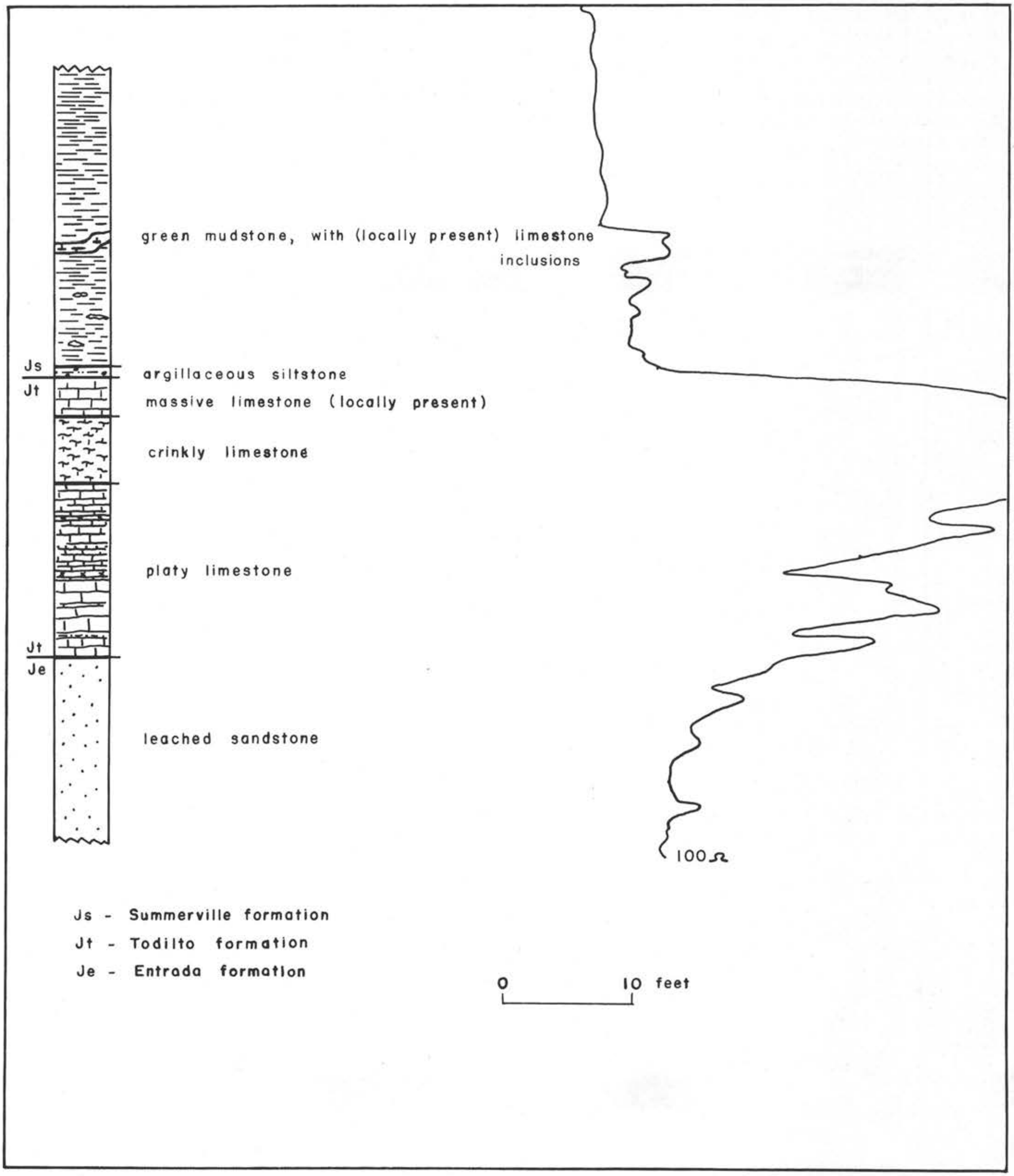


Figure 2

GENERALIZED COLUMNAR SECTION WITH RESISTIVITY LOG eral inches across, which are generally thought to be of diagnetic origin. Minute clay particles are present in extremely thin lenses or layers in the crinkly zone and probably contributed to the crenulations by providing zones of differential mobility during diagenetic readjustment (Rapaport, Hadfield, and Olson, p. 25). Locally, bedding in the crinkly zone is obscured by recrystallization, causing it in some locations to merge irregularly with the massive upper zone.

*Massive (upper) zone.* The massive zone, where present, is generally less than five feet thick and is a light gray to light grayish brown, medium-bedded to massive limestone. In many localities, the member is recrystallized, and in most localities it is highly discontinuous laterally and irregular in thickness. In some areas, a highly recrystallized and irregular upper zone is present which may actually consist of upper crinkly units with the characteristic crinkly bedding obscured by recrystallization.

Contacts between zones of the Todilto are irregular and frequently obscure, and often must be selected arbitrarily on the basis of gross lithology. Individual bedding surfaces throughout the limestone are generally discontinuous, although in some locations a gypsiferous marker bed has been traced for several hundred feet.

The Todilto conformably overlies the Entrada Sandstone with a contact that has been described as transitional (Rapaport, personal communication). Immediately beneath this contact a leached, varicolored, fine-grained, well-sorted sand stone unit of 10 to 3o feet thickness is present. Colors in this unit range from light gray to lavender, contrasting markedly with the predominant orange-brown sandstone of the Entrada. This coloration of the uppermost Entrada cuts across bedding and is apparently secondary (Rapaport, Hadfield, and Olson, p. 22).

The Todilto is overlain by the Summerville Formation with a highly irregular contact. The basal Summerville unit in the Todilto ore belt commonly consists of a six-inch to three-foot thick, light gray to varicolored, argillaceous siltstone, overlain by a mudstone unit of up to 20 feet in thickness which is predominantly green in color, but which changes irregularly and abruptly to reddish brown. Throughout the lower Summerville units, there are locally abundant crystalline limestone inclusions, ranging from pebble-sized bodies to large, irregularly lenticular masses (fig. 3).

In appearance and distribution these inclusions are highly irregular and variable and their origin is unclear. Gableman (p. 389) has described them as intertonguing features, although evidence, at least in some areas, suggests that they are detrital limestone resulting from erosional reworking of the Todilto during early Summerville time. Rapaport (personal communication) has cited evidence for such reworking in sec. 3o, T. 13 N., R. 9 W. where, locally, considerable portions of the Todilto are removed and where erosion patterns in the Todilto trend northeastward, correlating not with topography but with probable regional drainage during Todilto

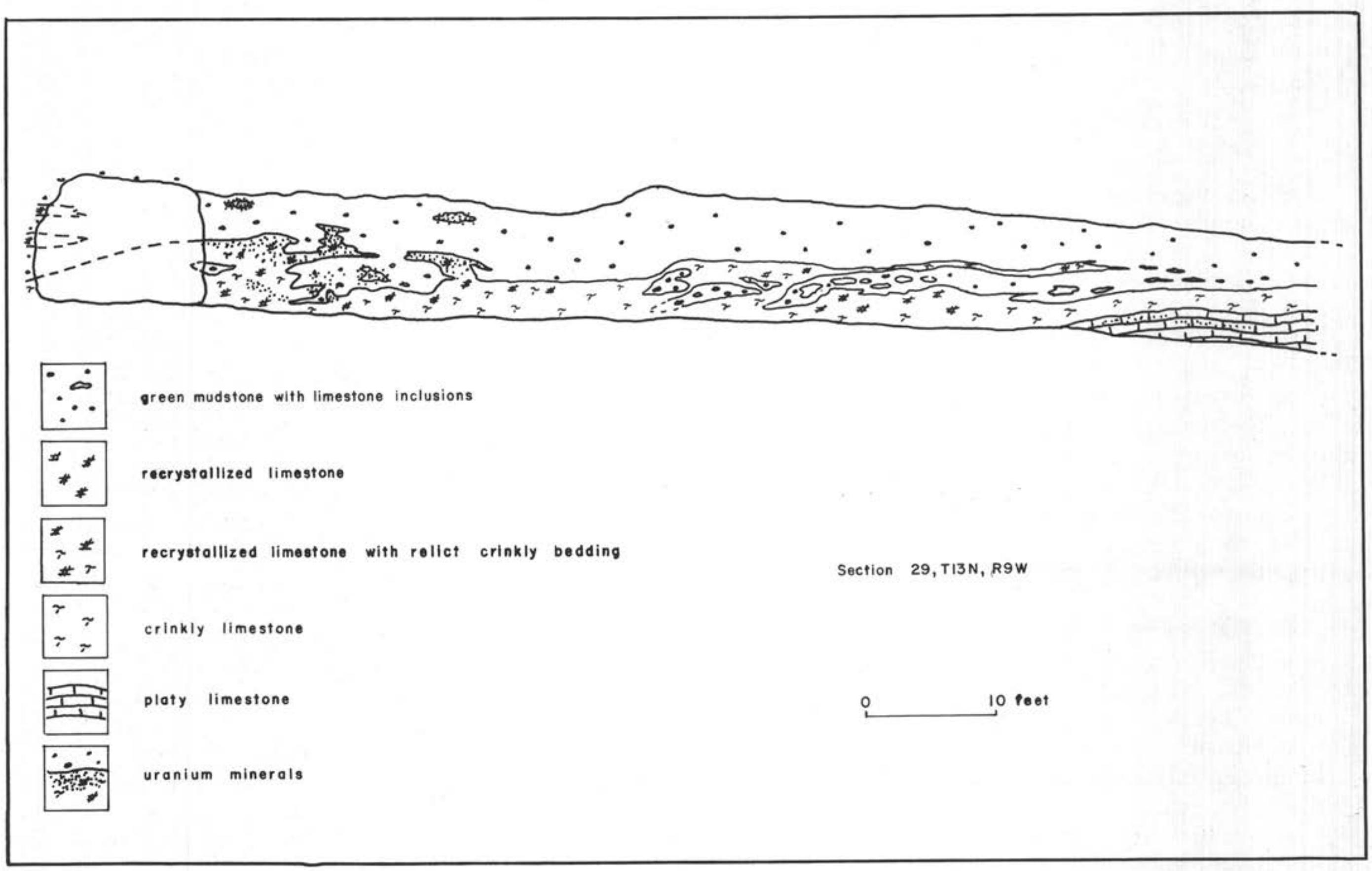


Figure 3

SECTION SHOWING WEST RIB OF DRIFT 10 SOUTH, FAITH MINE and Summerville deposition. Yet another possible origin is suggested in certain localities where apparent contortion and slippage along the Todilto—Summerville contact has seemingly broken and dragged portions of the upper Todilto into overlying Summerville units. Slippage along the Todilto-Summerville interface would not, however, seem to account for some limestone masses which occur as high as 2o feet above the upper Todilto contact. In all, it seems most likely that the inclusions are the result of erosional reworking of the Todilto, modified and distorted, in some areas by subsequent tectonic adjustments.

Important uranium deposits have been found in all units of the Todilto and some ore bodies have been found in the lower Summerville, generally being confined to contorted limestone inclusions. Ore in the uppermost unit of the Entrada has been reported in sec. 15, T. 12 N., R. 9 W.

## MINERALOGY

To avoid confusion of terminology, the following definitions are given of terms used by the writer:

*Primary uranium minerals or deposits.* Original minerals or deposits presumably deposited by hydrothermal solutions; that is, first arrivals.

*Primary-type uranium minerals or deposits.* Minerals such as pitchblende originally considered to be indicative of primary deposition but for which considerable doubt now exists as to origin.

*Secondary uranium minerals or deposits.* Any uranium minerals or deposits derived by reworking or modification of primary deposits (including alteration products).

### URANIUM MINERALS

#### Primary-Type Minerals

Pitchblende has been identified in most Todilto uranium deposits of the area and in the majority of deposits is probably the most economically important mineral. Pitchblende occurs in all the deeper deposits and in many of the shallower ones and replaces limestone in generally irregular disseminated patterns, blebs, bands, and veinlets. Ore outlines are frequently controlled by bedding, but replacements along minute fractures are common, as are replacements and fillings within brecciated, highly recrystallized, limestone masses. Replacement is selective and generally involves certain beds within a given area while excluding others. Laverty and Gross (1956, p. **zoo)** identified essentially two types of pitchblende ores, (I) those intergrown with fluorite and (2) those not intergrown with fluorite but in places associated with pyrite.

#### Secondary Minerals

Amorphous orange and yellow alteration products of pitchblende have been noted throughout the Todlito ore belt and have been tentatively identified as gummite.

Carnotite and tyuyamunite are perhaps the most abundant uranium minerals of the yellow oxidized type and are an important source of ore in the western part of the trend. Other, less abundant, secondary minerals have been identified by Gruner and Rosensweig and include uranophane, beta-uranotile, probably sklodowskite, and amorphous uranium vanadates resembling uvite and rauvite (Rapaport, 1952, p. o).

### ACCESSORY MINERALS

Fluorite is widespread in sparing amounts associated with the Todilto uranium deposits. It occurs in cleavable masses, columnar forms, and (possibly) dodecahedrons, in solution cavities, and in veins with calcite, pyrite, and barite. Fluorite replacing limestone is relatively abundant in sec. 25, T. 13 N., R. Io W., and fluorite in minute intergrowths with pitchblende has been described (R. A. Laverty and E. B. Gross, p. zoo). Most specimens are purple or dark purple in color, although colorless fluorite has been identified by Gruner (Rapaport, p. I I ).

Barite as tabular crystals or bladed masses occurs in solution cavities or veins, frequently with calcite, pyrite, and fluorite, as described above. Barite throughout the Todilto ore trend is a resinous yellow in appearance.

Pyrite is frequently present in minute grains and small cleavable masses associated with coarsely crystalline calcite and is often accompanied by fluorite and barite. Pyrite as irridescent coatings on calcite crystals has been found in sec. 29, T. 13 N., R. 9 W.

Hematite stains limestone in and around ore bodies and is most pronounced along fracture and bedding planes. Much of this hematite may be derived from the oxidation of pyrite.

Calcite recrystallized from limestone is abundant in solution cavities, veins, and brecciated limestone masses. There is apparently no direct association of calcite with uranium deposits, but calcite is generally most abundant in areas of folding and fracturing. The crystals are usually rhombohedral or scalenohedral and range from colorless to dark smoky gray.

Films and dendrites of black manganese oxides have been identified by Gruner but have not been demonstrated to be associated specifically with uranium deposits (Rapaport, p.
). Metahewettite has been reported in sec. 34, T. 12 N., R. 9 W. but is not known to occur alsewhere in the area.

### RECRYSTALLIZATION

Two apparently unrelated types of recrystallization are found in the Todilto. The first and probably earlier is a generally uniform, area-wide, fine-grained recrystallization of the crinkly member. This feature appears unrelated to either structure or uranium mineralization and has been attributed to various mechanisms. Gableman (p. 392) has considered it to be the result of widespread solutions of possibly hydrothermal origin. Rapaport (p. 25) has considered the feature to be produced during diagenesis, resulting from a more prolonged period of lithification, the action of percolating ground waters during diagenesis, or the decay of contained organic material generating $CO_2$ and encouraging crystal growth by reprecipitation of $CaCO_3$. That this recrystallization was produced during diagenesis seems likely, because of the general lack of association of the feature with volcanic centers and its widespread and generally uniform character.

A second, apparently later, type of recrystallization has produced coarse calcite along solutionways provided by faults, joints, brecciated and contorted zones, and sometimes bedding in any or all members of the Todilto. Frequently accompanying this coarse recrystallization is less coarse recrystallization of relatively large masses of limestone outward from the solutionways. Rapaport (p. 11) has considered this later type of recrystallization to be post-Zuni uplift (Miocene?) in age.

Recrystallization of the later type is common in and around ore deposits but seems to be more directly related to the solutionway provided by the structures which have localized ore deposits than to the deposits themselves. Many recrystallized fold and fracture structures have been noted which are barren of uranium minerals, and it seems likely that solutions that have produced recrystallization have been largely independent of solutions which have deposited uranium.

## STRUCTURE

### FAULTS

North- and northeast-trending faults of up to several hundred feet of displacement transect the area (fig. I ). These faults are normal and may have resulted from tensional forces accompanying the Zuni uplift. Gableman (p. 391) noted the proximity of the major fault zones to areas of greatest uranium concentration and suggested that the faults may have been vertical district feeders for hydrothermal solutions. Except, however, for the general association between the area of relatively great faulting and the Todilto ore belt, there appears to be no connection between faulting and ore. In this regard the following observations may be made:

1. No primary ore has been found in these faults, within the Todilto, and few Todilto ore bodies are located upon or immediately adjacent to the faults. At one location (sec. 16, T. 13 N., R. 10 W.) small ore bodies occur to within approximately 15o feet of a major northeast-trending fault, but there is no known uranium mineralization within or adjacent to the fault itself.
2. Todilto ore bodies occur within the outcrop belt at considerable distances from known faults.
3. A fault of relatively major size reportedly displaces ore in sec. 34, T. 12 N., R. 9 W., and a small fault has been noted in sec. 29, T. 13 N., R. 9 W., which displaces ore about one foot.

It would seem from the above that if there were originally a feeding of mineralizing solutions from the major faults, lateral migration of solutions or subsequent reworking of deposits has left the faults essentially unassociated with the present ore deposits. Moreover, it is apparent that some faulting or rejuvenation of faulting occurred subsequent to ore deposition.

### JOINTING

Joints are abundant in the Todilto Limestone and, through their general parallelism to the Zuni uplift, have been related to tensional forces resulting from the uplift of that structure (Ellsworth and Mirsky, 1952, p. 4). Ellsworth and Mirsky have related jointing also to folding, showing that the axial direction of folds is within a few degrees of the mean joint direction. It has also been suggested, though not conclusively established, that jointing may be more intense in areas of folding. Conjugate joint systems have been mapped in some areas (Ellsworth and Mirsky, p. 5), while in others only one principal joint direction has been found (Rapaport, personal communication). In most areas, more than one age of jointing is indicated.

It has been suggested that jointing may control ore deposits in the Todilto, either through fracture intersection control, or simply by the localizing influence on solutions of relatively heavily jointed areas. Work by Ellsworth and Mirsky (p. 5) tends to support this possibility since they have demonstrated definite elongations of ore bodies along one conjugate joint direction, with noses of ore protruding in the other joint direction. Other evidence is the existence in some areas of two ore zones separated vertically by barren beds and the seemingly great amount of jointing below ore outcrops.

Many deposits comprised mostly of uranium minerals of the yellow oxidized type seem obviously controlled by jointing, while in some primary-type deposits there is no apparent structural control except jointing. Rapaport (personal communication) has cited a N. Io W. joint set in the vicinity of sec. 3o, T. 13 N., R. 9 W., as controlling a downdip migration and redistribution of ore deposits and believes this set to be of later age than primary ore. Instances of ore terminating against joints are abundant throughout the Todilto ore trend, and in sec. 29 and 30, T. 13 N., R. 9 W., the removal of ore along fractures from within central portions of ore bodies has been noted. It seems likely, therefore, that earlier jointing, generally in conjunction with folding, controlled primary ore deposits and that jointing of possibly more recent age has controlled leaching and redistribution of deposits.

### FOLDING

Folding in the Todilto has received considerable attention owing to the relationship of folds to ore deposits. Unfortunately, various terminology has been used, and there has been a divergence of opinion regarding the nature of the ore-folding relationship and the origin of certain fold features. To further complicate matters, ore-structure relations have not seemed consistent throughout the ore belt. An attempt is made in this and the following section to classify the types of common folds in the Todilto and to relate them to types of associated ore deposits.

#### Regional Folding

Primary regional structure of the area is the Thoreau homocline which dips northeastward from the Zuni uplift into the San Juan Basin. At about right angles to this major structure are broad, related regional folds which plunge northeastward, approximately paralleling the major faults (Gableman, p. 391; figs. 1 and 4).

#### Minor Harmonic Folds

Striking at various angles to the regional folds are abundant, much smaller, harmonic folds which are probably also of tectonic origin. These folds generally involve the entire Todilto section and are usually traceable into adjacent formations (fig. 4). Sizes and shapes of these folds are variable, with widths generally ranging from several feet to 5o feet and lengths up to 25o feet. No particular pattern of orientation is evident, although a conjugate pattern has been noted in some areas, as has the tendency of the fold pattern to swing in a general manner with the Zuni uplift (Ellsworth and Mirsky, p. 4). These folds sometimes curve sinuously along strike and are often plunging.

#### Minor Disharmonic Folds

Generally smaller than the harmonic folds are highly irregular disharmonic folds which may involve any of the units of the Todilto or lower Summerville. These folds generally have very limited vertical extent and are overlain and underlain by flat-lying beds. Rock contortion on a very localized scale is frequently severe in minor disharmonic folds, and sizes, shapes, and orientations are highly variable and irregular. Frequently these folds merge with one or more other disharmonic folds.

Most folds of the disharmonic type in the Todilto can be classified generally into one of the following categories:

1. *Arch folds.* Small, relatively gentle, disharmonic arches are abundant in the upper crinkly zone (or in the upper massive zone, when it is present), although they are found in lower units as well. Small structures less than 8 feet in width and less than 15 feet in length are most numerous, although larger ones are not uncommon (fig. 4, pl. IA).
2. *Tight folds.* Small, tight, frequently recumbent, folds are found in all units of the Todilto and lower Summerville (fig. 4, pl. 1B). These folds range in size from near microscopic up to ten feet in width and 3o feet in length. Brecciation and complete recrystallization has occurred within certain of these folds, as has jointing and, sometimes, tiny thrust faults along the crests. In other folds of this type, however, the crests are thickened at the expense of the flanks, suggesting flowage. In some instances, tight disharmonic folds occur within the cores or along the flanks of larger, more gentle, arch folds.
3. *Bulge folds.* Less abundant than the above-mentioned folds are structures characterized by highly contorted, recrystallized, limestone masses portruding from the upper Todilto into the lower Summerville Formation (figs. 4 and 5). Although the origin of these structures is unclear, they seem to differ from disharmonic arch folds primarily only in the degree of rock contortion and recrystallization and are here considered fold structure. These features are typically quite narrow (less than 20 feet) but are sometimes surprisingly long. In sec. 29, T. 13 N., R. 9 W., several of these structures appear in plan as narrow, gently arcuate shapes ranging in length up to 200 feet. In one structure, relict crinkly bedding was found high in the recrystallized mass and in protruding limestone fingers.

## ORIGIN OF DISHARMONIC FOLDS

The origin of the disharmonic folds in the Todilto is unclear. Rapaport, Hadfield, and Olson (p. 38-39) interpreted the following as evidence that the folds were produced by creep of the unlithified Todilto Limestone down a gentle slope toward the basin under the weight of overlying Summerville silt and sands:

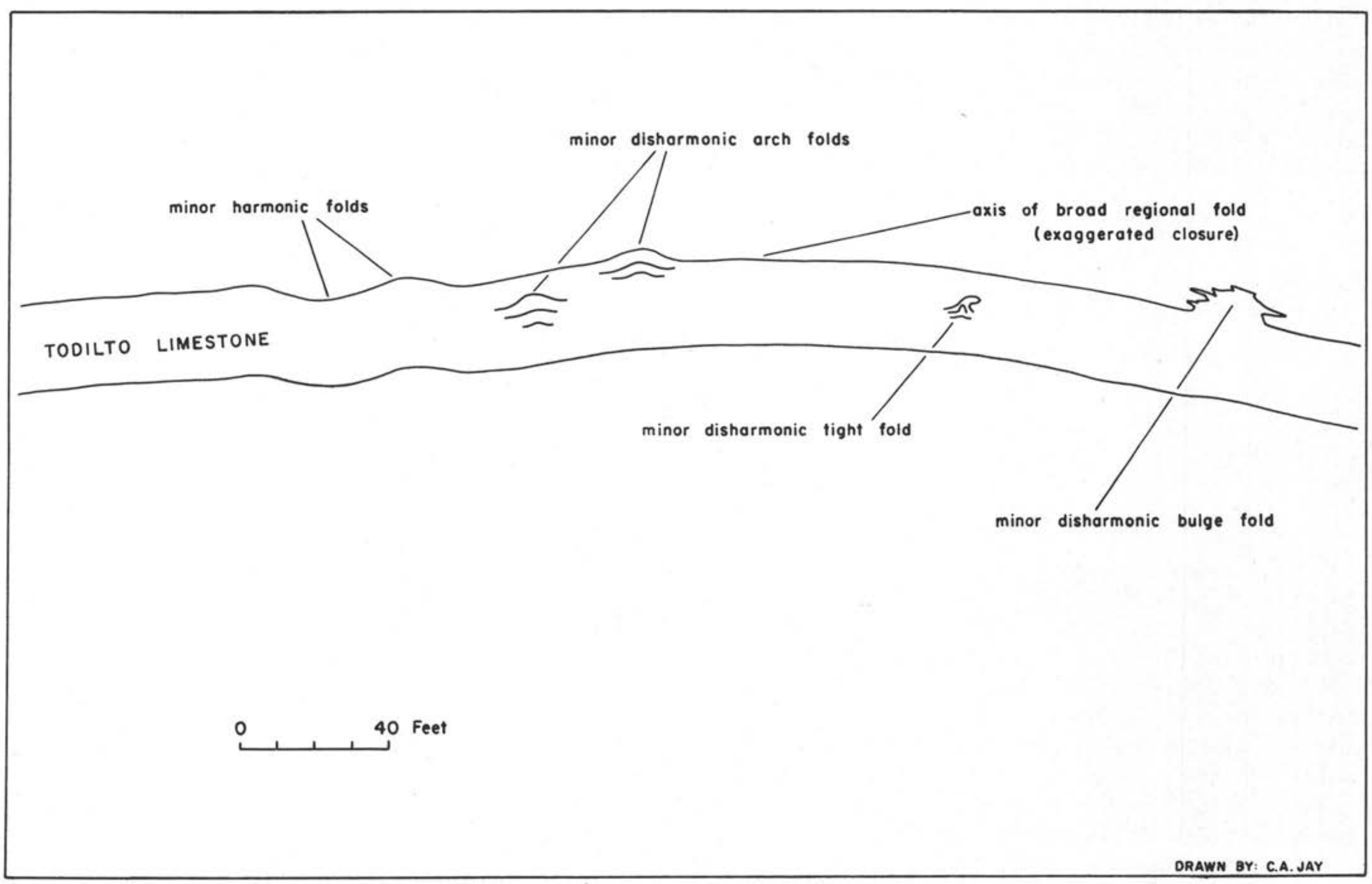


Figure 4

IDEALIZED SECTION ILLUSTRATING THE GENERAL TYPES AND RELATIVE SIZES OF COMMON TODILTO FOLDS

1. Axes of the folds show no evident relationship to regional structure.
2. The folds are confined almost entirely to the Todilto Limestone and the basal units of the overlying Summerville Formation.
3. The folds fail to show more pronounced fracturing than the flat-lying rock surrounding them.
4. Flowage is demonstrated by the thickening at the crests and troughs and thinning on the flanks.

Gableman (p. 389) has also suggested a diagenetic origin, noting as evidence the widespread occurrence of the folds and their consistent irregularity of axes.

The above evidence, however, does not conclusively establish a diagenetic origin. Moreover, although some disharmonic folds show flowage with no pronounced fracturing, others have been found that are extremely fractured or even brecciated. Another conflicting bit of evidence is the presence, in some localities, of slickensides along bedding planes of the Todilto. Rapaport (p. 5) noted the possibility of a tectonic origin, suggesting that the folds were created by differential stress during the Zuni uplift, the Todilto having responded by flowage between the more competent Entrada and upper member of the Summerville.

Plate 1-A

A. A minor disharmonic fold of the arch type in the wall of a small pit in the NW¼ sec. 25, T. 13 N., R. 10 W. Dashed line is the platy-crinkly contact. Fold is approximately eight feet across.

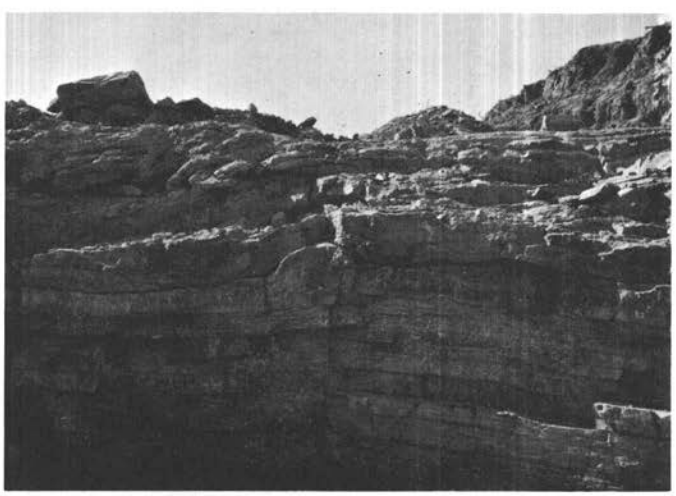

Plate 1-B

B. A minor disharmonic fold of the tight type in the wall of a small pit in the NW¼ sec. 25, T. 13 N., R. 10 W. Fold is approximately three feet across.

From the sum of the available evidence it would seem then that disharmonic folds of two different origins may be present; namely, ( 1) folds which suggest flowage without attendant fracturing and (2) folds which are fractured or brecciated and highly contorted structures (such as bulge folds) present along the Todilto—Summerville interface.

Folds of the first type might well be related to the widespread crenulation of bedding in the crinkly zone and were possibly produced, along with the crenulations, during diagenesis. Folds of the second type, on the other hand, seem most likely to have resulted from accommodation within the Todilto to tectonic stresses during the Zuni uplift and to possibly recurring slippage along the Todilto—Summerville interface.

## RELATIONSHIP OF FOLDING TO ORE DEPOSITS

### Regional Folds

The broad, regional folds of the area do not seem directly related to specific ore deposits. Of possible significance, though, is the location of the Todilto uranium trend within an area of relatively great regoinal folding and faulting. Also, Gableman (p. 392) noted that the major clusters of deposits are located within broad, relatively shallow synclines. The significance of this relationship is uncertain but has been interpreted as "indicating the accumulation of uraniferous solutions in structural sumps under the influence of gravity" (Gableman, p. 396).

### Minor Harmonic Folds

Certain ore deposits in the Todilto appear to be related to folds of the minor harmonic type. Ellsworth and Mirsky, whose studies included the mapping of the Todilto—Entrada contacts in sec. 19, T. 13 N., R. 10 W., sec. 25, T. 13 N., R. 1 o W., and sec. 9, T. 12 N., R. 9 W., found all the large ore bodies on those properties lying on anticlinal noses, and most of the small ore bodies on anticlinal noses or synclines. In addition, it was noted that the trend of all large ore bodies they examined conformed generally to contours of the Entrada. Gableman, too, has cited folds of the minor harmonic type as being related to economically important ore bodies (p. 389). In certain areas of the belt, however, the relationship of ore to these folds seems poorly pronounced, or even nonexistent. Rapaport (personal communication), in an early study of sec. 3o, T. 13 N., R. 9 W., observed that there was no evident association of mineralization with Tertiary structures. In sec. 29, T. 13 N., R. 9 W., and on other properties, folds of the harmonic type appear to have only a vague and inconsistent association with ore.

Throughout the Todilto uranium trend there are abundant minor harmonic folds with no associated uranium mineralization.

### Minor Disharmonic Folds

The association of uranium mineralization with minor disharmonic folds of the arch and tight types is widespread and seems consistent throughout the belt. In general, these folds tend to localize only small ore bodies, or to control centers of high-grade ore within large ore bodies. This characteristic seems to be the result of the usual small size of the structures, however, since the sizes of ore bodies, in general, appear frequently to be related to the size of associated structures or to the degree of rock contortion. Relatively large individual deposits are therefore occasionally found associated with unusually large disharmonic folds or sometimes with several small discordant folds which are closely related or merged.

In sec. 29, T. 13 N., R. 9 W., sec. 3o, T. 13 N., R. 9 W., and sec. 34, T. 12 N., R. 9 W., long, narrow, high-grade ore bodies are localized on disharmonic structures of the bulge type and in associated limestone fingers and lenses within the lower Summerville.

As with minor harmonic folds, numerous disharmonic folds are found throughout the belt with no associated uranium mineralization.

## ORE DEPOSITS

The belt of known major uranium deposits in the Todilto Limestone corresponds to the belt of Todilto outcrops bounded to the northwest by sec. 13, T. 13 N., R. I 1 W., and to the southeast by sec. 34, T. 12 N., R. 9 W. (fig. I ). Southwest from the uranium belt, the Todilto has been removed by erosion, while northeast, the Todilto is buried to depths which have thus far constituted an economic barrier to exploration. Principal ore deposits within this belt are conspicuously clustered in or around sec. 19, T. 13 N., R. 10 W., sec. 3o, T. 13 N., R. 9 W., and sec. 9, T. 12 N., R. 9 W.

Individual bodies of uranium in the Todilto are numerous, particularly in the centers mentioned above, but are generally small, the great majority containing less than 5000 tons of ore. Larger bodies are not rare, however, and two known Todilto ore bodies are reported to have exceeded 1 oo,000 tons (sec. 34, T. 12 N., R. 9 W., and sec. 19, T. 13 N., R. io W.). The grade of ore in Todilto deposits is usually less than 0.30 percent $U_3O_8$, but individual bodies of higher grade than 0.50 percent U3O8 are fairly numerous. The distribution and orientation of deposits seem to be generally random, except for the tendency to clusters around the above-mentioned centers. In limited areas, as in parts of sec. 25, T. 13 N., R. Io W., and sec. 29, T. 13 N., R. 9 W., small individual ore bodies are closely strung out, or roughly aligned, appearing as a string of individual ore bodies within a broad, mineralized, trend (fig. 6).

Ore bodies consisting principally of primary-type uranium minerals are most numerous, although in some ore bodies, particularly in the western part of the belt, yellow secondary-type minerals comprise most, or even all, the uranium values.

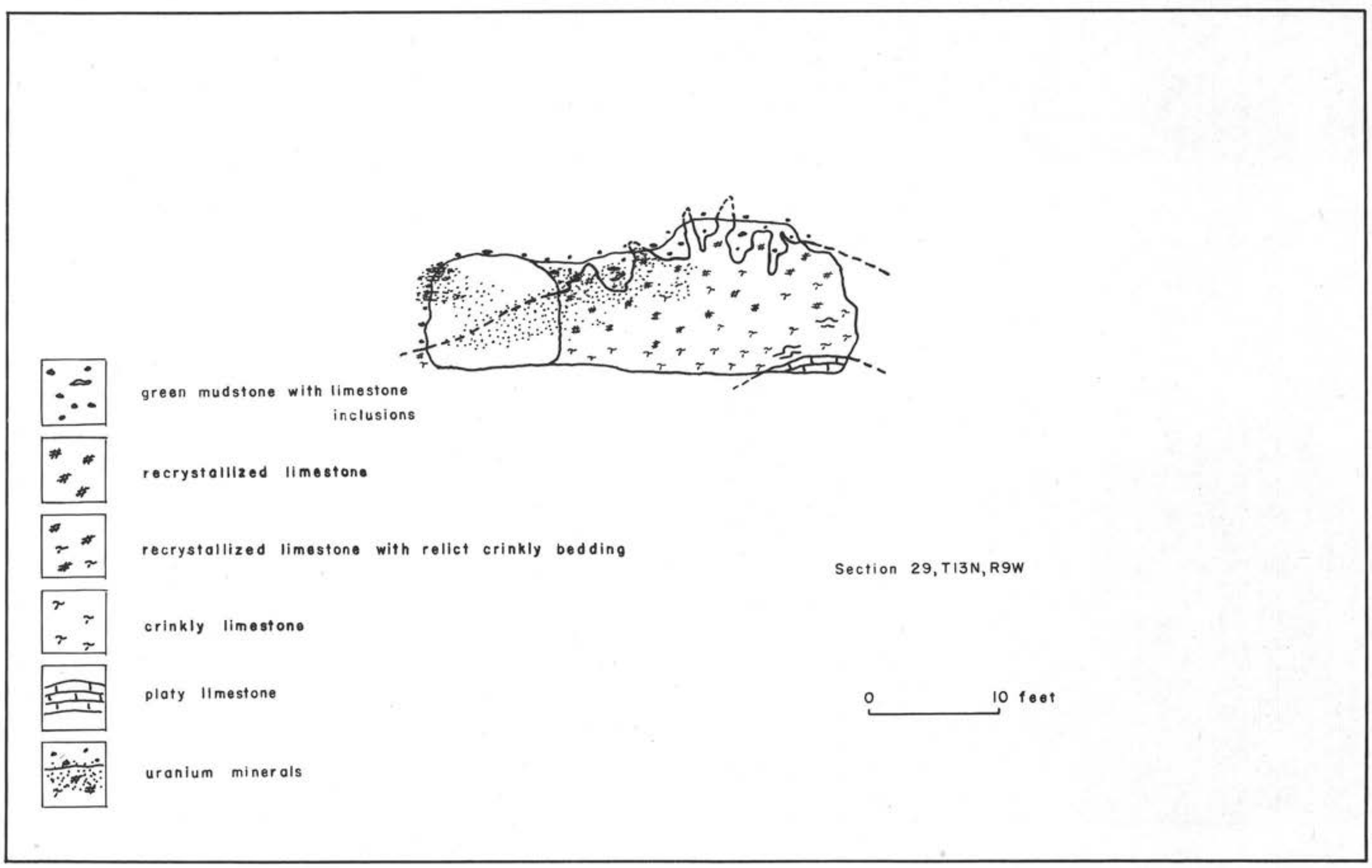


Figure 5

SECTION THROUGH BULGE STRUCTURE IN 10 SOUTH AREA FAITH MINE

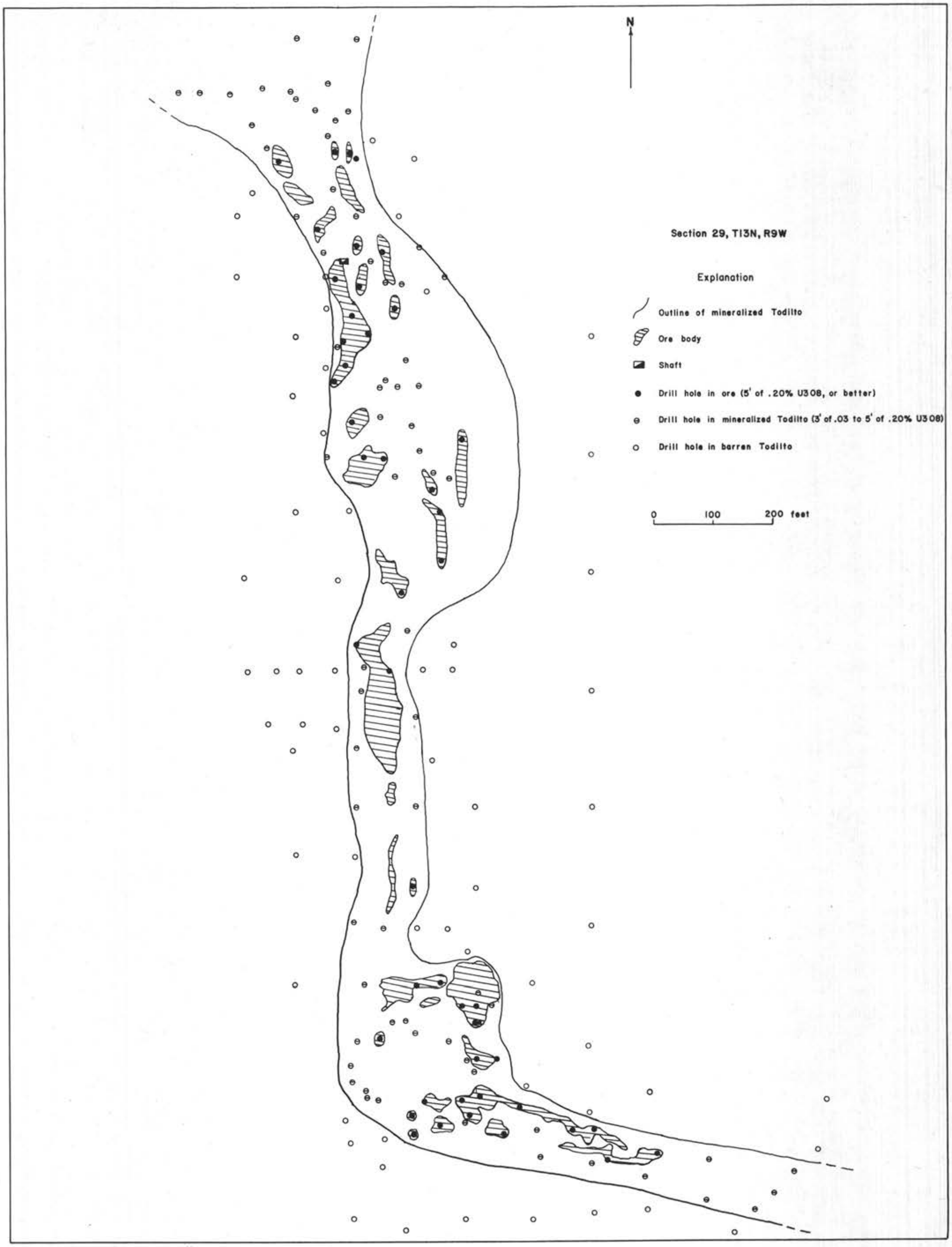


Figure 6

MAP OF THE MAIN FAITH ORE TREND

Shapes of individual ore bodies range from roughly oval to irregularly elongate and narrow. Gableman (p. 396) observed that primary deposits occur as narrow bodies and secondary deposits as irregularly rounded lenses more than 200 feet in maximum diameter, such as the Haystack (sec. 19, T. 13 N., R. 10 W.) and related ore bodies. Ore boundaries are frequently quite sharp in primary-type deposits and in some instances coincide with joints. In other instances, primary-type ore is found to finger or pinch out along selected beds. It has been noted that secondary ore bodies are generally more irregular in outline, with even short outward migration of secondary minerals tending to disrupt the sharp demarcation of primary bodies (Gableman, p. 396).

Most ore deposits seem related to certain of the numerous minor folds in the Todilto. In these fold-associated ore bodies, mineralization is sometimes most intense within, or is centered around, the most contorted portion of the fold and is usually elongate along the axis of the fold. In others, however, there is an apparent tendency for ore to be localized upon one flank of the fold, with ore rarely found on both flanks. Some deposits appear to be unrelated to folding, and in these, jointing may be the sole localizing influence. In some locations, as in sec. 29, T. 13 N., **R.** 9 W., important ore has been produced from fingers or thin, elongate, lenses of limestone within the lower Summerville. Such ore occurrences are sometimes within limestone fingers or lenses associated with bulge structures, while others are in limestone inclusions within the Summerville Formation, which appear unrelated to bulge structures.

## SPECIFIC PROPERTIES

*Section 13, T.* 13 *N.,* R. *11 W.* Six small uranium deposits have been mined by open pit in the northwest quarter of section 13. These deposits range in grade from subeconomic to low-grade ore and lie roughly in a northwest-southeast alignment. The largest deposit reportedly consisted of less than 2000 tons of ore.

*Section 19, T.* 13 *N.,* R.10 W. One of the largest ore bodies in the Todilto Formation was mined by open pit from the northwest quarter of section 19 and reportedly exceeded 100,000 tons. This ore body was approximately 1150 feet in length and ranged from 130 to 520 feet in width. Actual continuity of ore within these dimensions is unknown, however, and it is possible that the deposit consisted of two or more, closely spaced, smaller ore bodies. The deposit, as mined, was elongate roughly northwest-southeast and irregular in outline. Approximately 13 smaller ore bodies were mined from around the large deposit, and collectively the deposits formed a local northwest-southeast-trending belt. The smaller deposits ranged in size from loo to 500o tons of ore, and the average grade of all deposits reportedly ranged from 0.10 to 0.29 percent $U_3O_8$.

Ore deposits in section 19 were apparently localized within an area of relatively strong and numerous folds of the minor harmonic type. These folds generally strike and plunge northwestward, with some folds striking and plunging northeastward. Ore occurred primarily in the platy member at or near the base of the Todilto and consisted mostly of secondary minerals of the yellow oxidized type.

*Section* 24, T. 13 *N.,* R. 11 W. Several ore bodies have been mined by open pit from the northeast quarter of section 24. The largest of these was reportedly 640 feet long and from zoo to 145 feet in length. The ore bodies were oriented-generally northwest-southeast and were apparently related and similar to the northwest-trending belt of deposits in adjacent section 19.

*Section 18, T. 13 N.,* R. 10 W. Two or more ore bodies have been worked from two inclined shafts in the southwest quarter of section 18. These deposits were apparently isolated from the belt of deposits in sections 18 and 24 and contained greater amounts of pitchblende and barite.

*Section 17,T. 13 N.,* R. 10 W. One small, unworked, subeconomic uranium deposit is known in the northwest quarter of section 17.

*Section 16, T.* 13 *N.,* R. 10 W. Several small uranium deposits occur in the northwest quarter of section 16 and range in grade from subeconomic to low-grade ore. Two of these deposits have been worked by open pit, and all deposits appear localized within a zone of relatively abundant joints and disharmonic folds. Principal uranium minerals are pitchblende and gummite (?), accompanied by relatively abundant barite, pyrite, hematite, and coarse calcite. Considerable jointing, brecciation, and recrystallization of limestone accompany nearby northeast-striking faults; however, the faults appear barren of uranium.

*Section* 22, *T. 13 N.,* R. IoW. One small, isolated, uranium deposit is known in the northeast quarter of section 22 and has been worked by open pit. Ore minerals consisted primarily of pitchblende and gummite (?) and were apparently localized by a minor disharmonic fold of the arch type in the upper Todilto.

*Section* 23, T. 13 *N.,* R. 10 W. Several ore deposits have been worked from near the south section line in the southeast quarter of section 23. These deposits reportedly ranged from 30o to 15,000 tons of ore and apparently were related to deposits on nearby sections 25 and 26.

*Section* 24, T. 13 *N.,* R. 10 W. Four small, unworked, uranium deposits are known in the southeast quarter of section 24 and are believed to be subeconomic.

*Section 25,* T. *13 N.,* R. 10 W. Known uranium deposits in section 25 probably exceed 5o in number and occur throughout practically the entire part of the section underlain by Todilto Limestone. The great majority of these deposits has been mined out, although some work on the property continues at this time. Mining has been by open pit throughout the south, central, and west parts and by vertical shaft near the north section line.

Distribution of deposits in the south and central parts of the section appears generally random, with shapes and orientations of individual ore bodies highly variable. Near the north section line, however, a distinct east-west orientation and alignment of individual deposits is evident, suggesting a trend pattern of distribution, such as in sec. 29, T. 13 N., R. 9 W. The largest individual ore bodies occur within this trend, with the largest being approximately 1300 feet long and ranging in width from 5o to 200 feet. Average grade of ore bodies throughout the section has reportedly been from 0.10 to 0.38 percent $LU_3O_8$.

Less structural deformation is evident in section 25 than in most other areas of the Todilto ore trend, although certain of the few harmonic and disharmonic folds which are present do appear to localize ore bodies. Jointing may have been the principal ore control, however, and Ellsworth and Mirsky (p. 5) noted the emphasis of two right-angle directions in one large ore body, suggesting to them control by a conjugate joint system.

The principal ore minerals in section 25 are pitchblende and gummite (?), which occur in all units of the Todilto, and all the usual accessory minerals have been noted. Fluorite is particularly abundant, occurring mostly as replacements in limestone.

*Section* 26, T. 13 *N., R. 10 W.* Several ore bodies have been mined by open pit and inclined shaft from the northeast quarter of section 26. The largest of these bodies was reportedly 7000 to 8000 tons of ore. In geologic characteristics, the ore bodies apparently were similar to those in adjacent section 25, including the particular abundance of fluorite and the indications of control of ore by conjugate joint sets (Rapaport, personal communication).

*Section* 3o, T. *13 N.,* R. 9 W. As in adjacent section 25, ore deposits in section 3o are densely distributed and probably exceed 5o in number. There is no evident pattern of distribution, although many of the large deposits are elongate in an approximate north-south direction. The largest known individual deposit is perhaps the Flat Top ore body in the southeast quarter of the section. This deposit is approximately 42o feet long with an average width of approximately 170 feet. Mining has been by open pit in the southwest quarter of section 3o and by vertical and inclined shafts on the remainder of the section. One open pit and three shafts are known to be active at this time.

The following geologic descriptions are based on studies and observations at the Dalco shaft, in the northwest quarter of section 3o, as reported by Robert G. Coucher of S and A Mining Company (personal communication):

1. Pitchblende and gummite (?) are the principal ore minerals, although a few small ore bodies have been mined which consisted primarily of yellow oxidized-type uranium minerals. Most abundant accessory minerals are calcite, pyrite, and hematite. Barite is comparatively scarce, and fluorite is apparently absent.
2. Ore occurs in all units of the Todilto and in limestone lenses within the lower Summerville Formation. The platy member of the Todilto is typically seven feet thick, the crinkly zone two feet thick, and the upper massive zone eight to twenty feet thick.
3. Ore at the Dalco shaft occurs principally in association with minor disharmonic folds of the arch and bulge types. Considerable ore has been found in a series of subparallel, northwest-trending, bulge folds and in contorted limestone lenses within the lower Summerville Formation.
4. Ore bodies frequently terminate along leached joints, and ore has been removed along joints from within interior parts of ore bodies.

Both Coucher and Rapaport (personal communications) reported little or no association of ore with harmonic folds in section 3o, and Rapaport has noted considerable pre-Summerville erosion of the Todilto in parts of the section.

*Section* 29, T. *13 N.,* R. 9 W. Known uranium deposits in section **29** are confined essentially to the central and south-central parts of the section and are presently being worked through two vertical shafts. These deposits, in general, show a pronounced trend of distribution which appears to be unusual in Todilto ore deposits. The trends consist of long, narrow, belts of weakly mineralized ground within which are numerous small, similarly oriented, ore bodies (fig. 6). Numerous minor disharmonic folds are present within the trends and are generally oriented with the trends. Individual ore bodies, in general, are localized by certain of these individual folds. The largest known ore body was about 25o feet long, with a maximum width of 6o feet and an average thickness of 15 feet. This ore body was localized upon an unusually large fold of the minor disharmonic arch type, which was contorted internally by several related tight-type folds.

Considerable ore has been mined on the property from disharmonic folds of the bulge type and from contorted limestone lenses within the lower Summerville Formation. In general, ore bodies of this type have been found to be extremely narrow, elongate, and unusually high in grade. Other ore has been mined from disharmonic folds in the lower units of the Todilto, and in certain instances, such ore has underlain ore bodies in bulge folds within the top of the Todilto or in contorted limestone lenses within the lower Summerville.

The principal ore minerals are pitchblende and gum-mite (?), and all the usual accessory minerals have been noted. Fluorite is widespread in small amounts in solution cavities and veinlets but has not been found replacing limestone.

Mining in section 29 is carried out to depths of 450 feet, and the deepest part of the mine workings lies beneath the water table. In this location, the Todilto is a surprisingly good aquifer, and as much as 35o gallons of water a minute must be pumped from the formation to permit mining operations.

*Section* 32, T. 13 *N.,* R. 9 W. Two small uranium deposits are known in the north-central part of section 32. The larger of these is presently being developed through an inclined shaft.

*Section* 33, *T. 13 N., R. 9* W. Several small uranium deposits have been worked by open pit in the southwest quarter of section 33. These deposits range in grade from subeconomic to low-grade ore, with the largest having provided probably less than 400 tons of ore.

*Section* 34, T. *13 N.,* R. *9* W. Several closely spaced ore bodies of moderate size have been mined from the southwest quarter of section 34 by inclined shaft.

*Section 4,* T. *12 N.,* R. *9* W. Approximately 18 individual ore bodies have been mined from section 4 by open pits and by adits driven beyond the walls of pits, and some small-scale mining operations are being conducted at this time. The largest ore body was reportedly 1500 feet long and from 10 to 5o feet wide. This ore body was elongate northeast, and ore deposits on the section appear collectively to form a local belt trending generally north-south. Control of mineralization was apparently by minor folds of both the harmonic and disharmonic types.

Ore, mostly of pitchblende, occurs in all units of the Todilto, with the majority perhaps in the upper units. Some occurrences of all the usual accessory minerals have been reported.

*Section 9,* T. **12** *N.,* R. 9 W. About 25 individual ore bodies have been mined from section 9 by open pit and by adits driven from the Todilto outcrops. These deposits reportedly ranged up to 2000 tons of ore and were generally low in grade. These deposits apparently were similar to those in adjacent section 4.

*Section 15,* T. 12 *N., R.* 9 W. Two small, isolated ore bodies have been mined by open pit from the west half of section 15. One of these deposits reportedly consisted of pitchblende in the upper several feet of the Entrada Sandstone and is said to have contained 1000 tons of nearly one percent U308.

## ORIGIN

Fluorite in Todilto uranium deposits has been considered as evidence that the deposits were influenced by hydrothermal solutions. Other evidence suggesting hydrothermal influence includes

(I) the association of uranium and fluorite with barite and pyrite in Todilto ore deposits, and the similarity to mineral suites in veins of the Zuni crystalline complex (Rapaport, personal communication),
(2) the general proximity of the Todilto uranium trend to centers of volcanic activity, and
(3) the presence of faults which could have acted as feeders.

Evidence which, however, tends to conflict with the above is

(I) the absence of vein quartz,
(2) the absence of rock alteration,
(3) the proved ability of pitchblende, barite, and pyrite to form under temperatures associated with normal ground waters,
(4) the relative lack of hydrothermal features or evidences in nearby sandstone deposits of the district, and
(5) the apparent lack of association of most individual Todilto uranium deposits with faults and volcanic centers.

Thus it is seen that the case for hydrothermal influence on ore deposits rests most strongly on the chemistry of the mineral fluorite, which is considered insoluble under conditions associated with ordinary ground water. However, Gruner (1954) noted that fluorite has been reported in places under conditions which rule out hydrothermal sources, such as salt domes and in the uranium-bearing Phosphoria Formation. It seems unlikely, though, considering the known chemistry of fluorite and the nature of fluorite occurrences in the Todilto, that the fluorite in Todilto ore deposits could have been deposited by ordinary ground water. In addition, the limited distribution of this mineral and its presence as crystals in solution cavities seems to rule out a syngenetic origin. Thus, despite the lack of other strong supporting evidence, some hydrothermal activity is presumed to have influenced Todilto uranium deposits and, most likely, was the source of the uranium, fluorine, barium, and possibly other ions.

The lack of rock alteration and vein quartz in Todilto ore deposits suggests diluteness of the hydrothermal solutions. This "weakness" could be attributed to the magmatic source or to dilution resulting from long migration before deposition of the ore deposits. The possible comingling of hydrothermal solutions with ground water has been mentioned by Rapaport (p. 19). That lateral feeding or migration has taken place is suggested both by the termination of ore against the underlying Entrada Sandstone (Gableman, p. 396) and the lack of association of Todilto ore deposits with known faults and volcanic centers.

The location of the faults or fissures through which hydrothermal solutions ascended is largely a matter of speculation, since no direct evidence has been found associating the known faults in the area with primary uranium deposits, and since the distance of lateral migration of the hydrothermal agents is unknown. It is assumed, however, that hydrothermal agents could have been fed through the faults which transect the Todilto uranium trend (Gableman, p. 391) or through faults in the Zuni Mountain area with subsequent downdip migration. The age of these faults may be inferred from their apparent relationship to the Zuni uplift, which has been termed late Eocene to late Miocene (Rapaport, Hadfield, and Olson, p. 46). The age of primary uranium mineralization may thus be comparatively established through its presumed relationship to these faults. This relative age is further indicated by the apparent localization of primary-type ore, in some areas, on minor harmonic folds which may have been produced by forces of the Zuni uplift.

Certain Todilto ore deposits comprised of yellow oxidized-type minerals seem obviously to have resulted from relatively late redistribution of primary minerals by ground water. However, pitchblende intergrown with fluorite and pitchblende without fluorite (and in places associated with pyrite) have been identified as distinctly separate types of ores (Laverty and Gross, p. zoo), and it seems possible that the second of these types may also result from redistribution by ground water.

## FEATURES OF EXPLORATION AND MINING

The following is a summary of geologic guides to Todilto ore deposits:

1. *Accessory minerals.* The accessory minerals fluorite, barite, and pyrite are commonly associated with uranium mineralization but are usually far less abundant than the uranium minerals themselves. An increase in hematite coloration usually accompanies uranium deposits, and being frequently more dispersed, it may be used as a general guide to ore.
2. *Recrystallization.* Extensive recrystallization (of the later type) occurs in areas of structural deformation and is thus useful for defining areas favorable for ore.
3. *Folding.* Minor folds of the harmonic type may be determined by the mapping of the Todilto—Entrada contact and within certain areas of the Todilto ore trend, are indicative of areas favorable for ore. Minor folds of the disharmonic type appear to be favorable for ore throughout the belt but are generally not detectable by known exploration techniques. The exceptions are arch folds and bulge folds in the top of the Todilto, which may frequently be detected by the mapping of the upper Todilto surface, or of the Todilto thickness, from drill-hole data obtained on close centers.

   The orientation of folds can usually be used to determine the probable direction of elongation or trend of ore bodies with which they are associated.

   Synclines of the broad regional type may constitute areas more generally favorable to a dense concentration of uranium deposits.
4. *Limestone lenses in the Summerville.* Lenses of limestone in the lower part of the Summerville Formation are generally favorable for uranium deposits and may be detected from drill-hole data.
5. *Jointing.* Intensely jointed Todilto may be favorable for

ore, although it has not been conclusively established. The mapping of joints, along with evidence from folding, may be useful in determining the probable direction of elongation of ore bodies.

6. *Areal trends.* Within certain limited areas, the tendency of individual deposits to align, or to be strung out within a broader trend of mineralization can be a useful guide in exploration.
7. *Eroded Todilto.* Rapaport (personal communication) has reported as unfavorable for ore deposits Todilto from which the crinkly zone has been eroded.
8. *Halos of mineralization.* Ore bodies frequently have lateral extensions or halos of relatively weak uranium mineralization. Many areas or patches of weak mineralization are present, however, with no associated ore.

Exploration drilling by wagon and rotary drills has been the most widely used and most effectvie method of exploration, although much exploration by trenching and some by hand-dug pits has been carried out where the depth of Todilto burial is slight. Preliminary drilling has usually been accomplished on a grid basis with holes spaced on centers of 10o feet or greater. Holes intersecting mineralized ground have then been closely offset by additional holes. Small but high-grade ore bodies have been completely missed by holes 5o feet apart, however, and a 2.5-foot hole spacing is frequently necessary to properly explore favorable ground.

Detailed geoglogic mapping and radiation surveys to determine favorable ground prior to drilling and the careful interpretation of drill-hole data to determine further geologic guides during drilling are considered highly useful tools to exploration. These tools are particularly useful where the depth of overburden, or other considerations, makes close-spaced preliminary drilling uneconomic.

The relatively small size of most known Todilto ore deposits has generally limited exploration and mining in this formation to depths of less than 450 feet. Where the thickness of overburden has been less than 3o feet, many of the smallest deposits have been successfully stripped or mined by open pit. At greater depths, the presence of relatively large, high-grade, or numerous ore bodies has made underground mining feasible in certain locations. Development of ore in these underground operations has been by vertical or inclined shafts or, more rarely, by adits from either Todilto outcrops or the edges of open pits. Underground mining methods have included square-set stoping in the thicker ore bodies and room and pillar mining in the wider ore bodies, but open stoping is most common.

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# *Limestone Reefs as an Ore Control in the Jurassic Todilto Limestone of the Grants District*

BOBBIE L. PERRY


## ABSTRACT

Uraninite ore deposits of the Todilto Limestone in the Grants district are associated with nonbedded, coarsely crystalline, limestone masses within the thin-bedded limestone formation. The coarsely crystalline structures have previously been considered anticlinal folds containing recrystallized cores. The structures are considered by the author to be bioherms, probably of algal origin.

The uranium minerals are concentrated along the edges as well as within the bioherm or reef. Three types of subordinate structures, often ore-bearing, are associated with the reef edges:

(1) Small asymmetric folds are often developed in the lower off-reef beds by plastic upwarping adjacent to the reef edges.

(2) Off-reef zones of sedimentary breccia or reef talus are developed adjacent to certain steep reef edges.

(3) Off-reef beds of detrital material are developed in the fore-reef areas.

These features are frequently misinterpreted as the major ore control, while the true controlling structure, the reef edge, remains unrecognized.


## INTRODUCTION

The Todilto Formation is a thin but persistent Jurassic limestone and gypsum sequence in the San Juan Basin of northwestern New Mexico. This report considers only that part of the formation within the uranium-producing area of the Grants district. Within this area, the formation is somewhat variable in thickness, seldom exceeding 25 feet. Overlying the Todilto is the Summerville Formation, which varies from a shale to a shaly sandstone. The Todilto rests upon the Entrada Sandstone, a reddish brown, wind-blown sandstone. A thin, highly oxidized zone is sometimes present in the extreme upper part of the Entrada Sandstone, probably marking a pre-Todilto erosional surface.

The lithologic changes within the Todilto Limestone are distinct and furnish an excellent tool for dividing it stratigraphically into three units as follows: (1) a lower, very fine-grained, thin-bedded limestone, locally termed "platy zone," (2) a middle, extremely thin-bedded limestone possessing a wrinkled or crepelike appearance, locally termed "crinkly zone," and (3) an upper, massive, occasionally crudely bedded, coarsely crystalline limestone, locally termed "recrystallized zone."

The author feels that the terms "platy" and "crinkly" are well chosen in that they are accurately descriptive of the two lower zones; however, he feels that the field evidence is insufficient to suggest that the massive unit has been recrystallized. This zone also should not be termed merely the "upper zone," because in some areas this lithologic facies comprises almost the entire thickness of the formation. The terms "coarsely crystalline zone" or "massive zone" are suggested as more descriptive and less misleading designations. Though the various units are easily identified, it is sometimes difficult to determine the exact contact between the platy zone and the overlying crinkly zone. The massive and crinkly zones are completely absent in some areas, particularly those areas in which the formation becomes thin.

## ORGANIC STRUCTURES

This discussion is principally of the ore-controlling structures as they pertain to the primary uranium minerals rather than the secondary minerals found in fractures, vugs, and other voids. The secondary occurrences are important, as indicated by the intense coatings and fracture fillings in several areas. Mineable deposits of secondary uranium minerals have also been located within the extreme upper part of the Entrada Sandstone where the overlying Todilto Limestone has been severely weathered. The deposits of secondary minerals do not, however, reflect the original ore controls and for this reason are not considered further.

Upon first examination, there appear to be several different types of ore-controlling structures present within the Todilto; however, close examination shows that all primary mineral deposits occur within or closely associated with humps or long moundlike structures composed of coarsely crystalline limestone. The structures vary from moundlike features a few feet in diameter to long, sinuous, ridgelike structures half a mile or more in length. These structures have been created by a thickening of certain crudely bedded zones within the formation rather than by a folding or upwarping (fig. i ). The entire structure, as exposed in the photograph, is composed of the coarsely crystalline facies. Erosion and weathering have removed the overlying Summerville beds. In many instances, the crystalline limestone masses are interbedded with the overlying Summerville sediments, forming a transitional zone between the two formations.

Such ore-controlling structures as illustrated in Figure 1 are of organic origin. The author has found by field examination that the Todilto Formation contains bioherms and biostrome of several types. Many of these structures, more specifically, should be classified as reefs, since they meet most of the requirements suggested by Cumings (1932).

The specific organisms of the reefs cannot be determined;

however, in the author's opinion the reefs are of algal origin. Any attempt to investigate relic organic features with a microscope was thwarted by the extremely coarsely crystalline texture of the coenoplase. This is not unusual; even in present-day coral reefs, according to Twenhofel (1919), algae frequently contribute more to the build-up of a reef than do the corals, yet remain unrecognized, as evidenced by the name "coral" reef.

The ore-controlling structures within the Todilto Formation have acquired a reputation among miners and geologists for being erratic and unpredictable. This is true if one attempts to relate these ore-controlling structures to faulting, folding, or regional tectonics; however, when viewed as reefs and related to the conditions controlling reef growth, they are considerably more understandable. It must be realized that no two reefs are exactly alike, because the many varying conditions imposed upon a growing reef are reflected in its size and shape.

## REEF TYPES

All reefs examined were at least slightly mineralized. Regardless of the grade of ore, the fore-reef edge is almost without exception of higher grade than the rest of the reef. In many instances, this mineralized zone is partly shared by the fore-reef beds of detritus adjacent to the highly mineralized reef edge. This phenomenon is very important to some mine operators, since the fore-reef edges and a few feet of adjoining off-reef material are the only mineable portions because of the low grade of the remainder of the reef.

Figures z and 3 represent a particular type of reef edge development very common in secs. 4 and 9, T. 12 N., R. 9 W., as well as several other locations. Figure z was sketched from an exposure near the eastern end of the long east-west open pit on the Red Bluff No. 8 Claim, sec. 4, T. 12 N., R. 9 W. Figure 3 was photographed in an open pit in the extreme northern portion of sec. 9, T. 12 N., R. 9 W. In both figures, remarkably smooth flexures adjacent to the actual reef edge

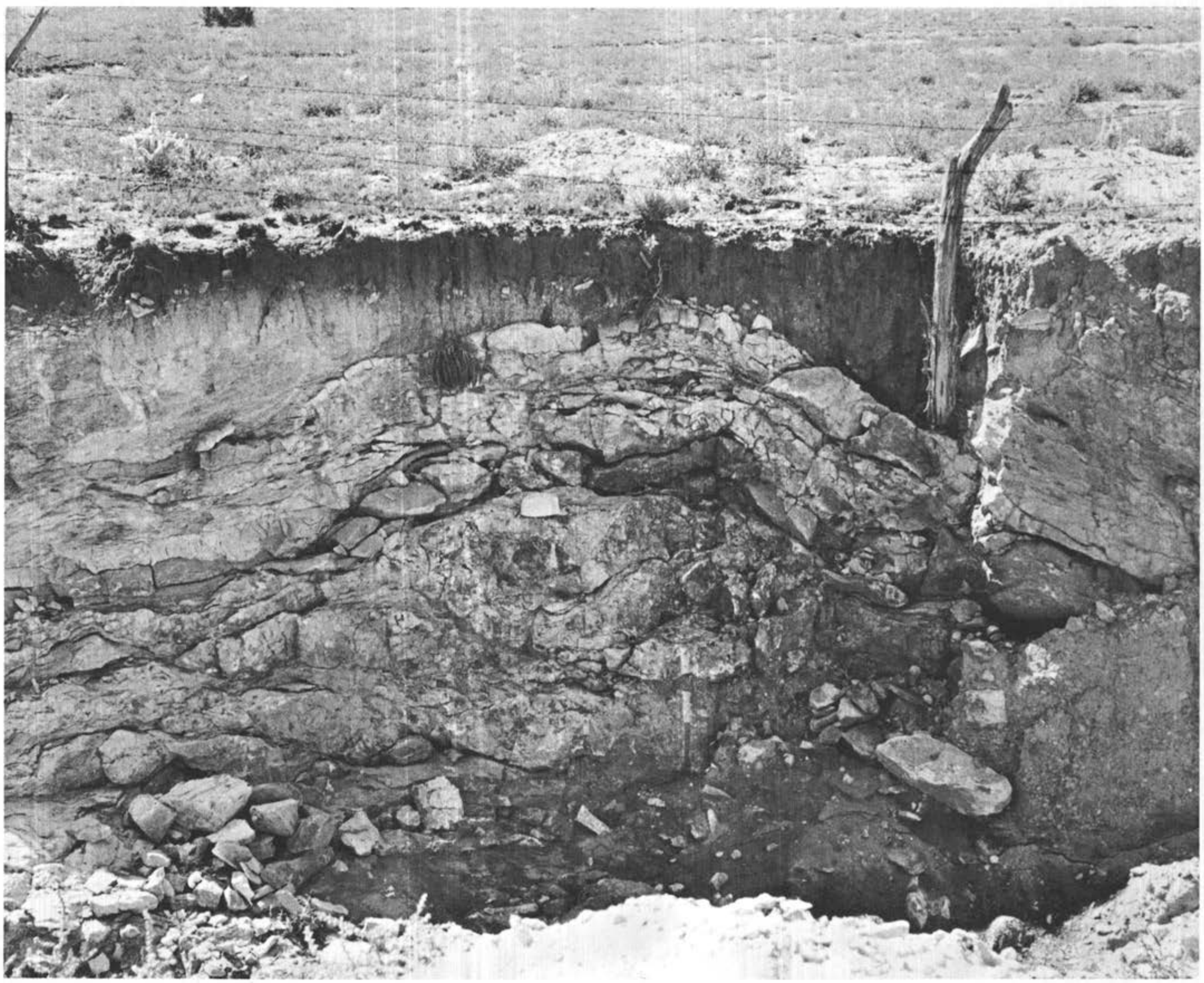

Figure 1

PART OF A REEF GROWTH IN SEC. 4, T. 12 N., R. 9 W.
(For scale, note White Mine Cap.)

may be seen. These folds have been termed "ore-controlling structures" by many workers in the Todilto; however, the true ore control in this situation is the reef edge. In mining these ore bodies, the fold structures may be followed with excellent results owing to the fact that the folds are developed immediately adjacent to the large reef edges. The reef edge would have been mineralized and mineable regardless of the presence of the off-reef flexures. This is proved by the many instances where productive reefs are found without the accompanying flexures. These small folds, however, are extremely interesting regardless of their bearing on mineralization. The folds are normally several inches to a few feet across, as indicated by Figures 2 and 3. They are normally very smooth, well-formed, asymmetrical folds, occasionally fractured near the crests. In all places observed by the author, the fold axis is either tilted or completely overturned, always toward the reef mass. The bedding planes exhibit well-formed slickensides in the more intensely folded zones, and if an individual bed is followed, it is observed to thin or pinch beneath the reef.

The author's explanation for these flexures is simply that they were produced during diagenesis by the squeezing of the unconsolidated sediments directly beneath the reef mass, as indicated in Figure 4. The force created by the weight of the reef was resolved into horizontal forces when acting against the consolidated underlying Entrada Sandstone. It is interesting to note that large reefs, which were established and began to grow upon several feet of underlying lime sediments, commonly acquired these peripheral flexures in the off-reef strata. Conversely, those reefs which obtained a "foothold" and thrived almost directly upon the underlying firm Entrada surface exhibit no such flexures in their off-reef facies.

Sedimentary breccia or reef-talus development, particularly along steep fore-reef edges, is another common reef accessory. Fore-reef breccia zones are well developed in many places in the Todilto Limestone. The breccia zones occur adjacent and parallel to the steep seaward margins, as shown in Figure 5. The individual breccia particles are subrounded to rounded, are usually three feet to a few inches in diameter, and are composed of coarsely crystalline massive limestone. In many places, such as the Haystack Mountain Development Company Section 25 mine and the Rimrock mine, the reef edges and individual breccia particles are well mineralized. It is interesting to note that many completely isolated breccia boulders are highly mineralized; yet, the surrounding shales contain no uranium minerals. However, when the breccia fragments are enclosed by reef detritus, it is common for both the detrital material and the breccia to be mineralized.

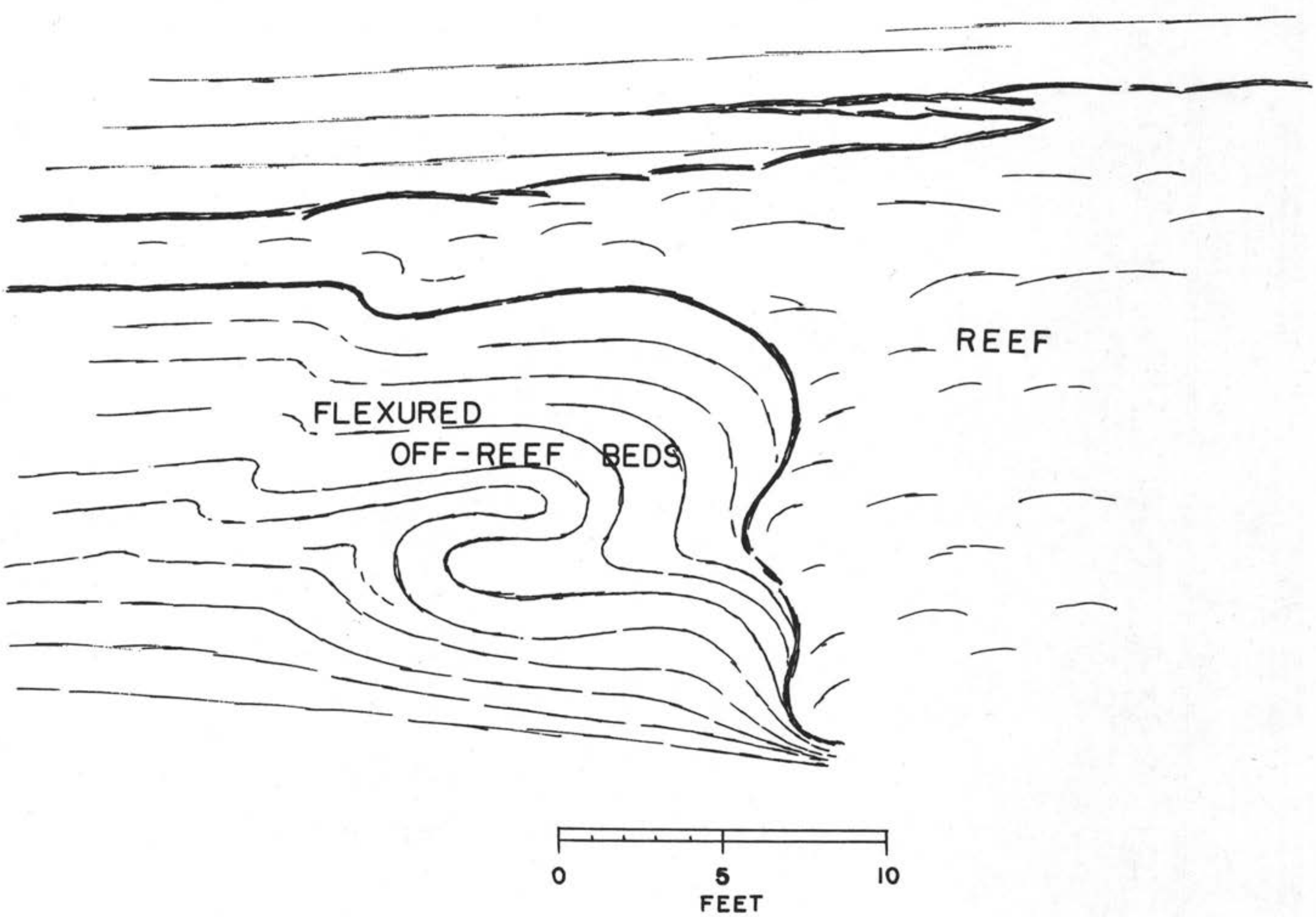


Figure 2

SECTION SHOWING TYPICAL REEF EDGE AND OFF-REEF FLEXURES
(Drawn from an exposure in an open pit in the south portion of sec. 4, T. 12 N., R. 9 W.)

Two slightly different types of breccia zones are suggested in Figures 5 and 6. It will be noted that in Figure 5 the breccia zone appears to have been formed primarily by the slumpage and caving of an extremely steep reef edge, and as would be expected, the breccia boulders are large and rather angular. The boulders are mineralized but are enclosed in an unmineralized shale. The breccia development shown in Figure 6 was probably produced by the gradual eroding away of the reef edge by wave action. These breccia fragments are more rounded and smaller than those illustrated in Figure 5. The breccia zones contain considerable fine-grained detrital material, and consequently both the breccia and smaller detritus are mineralized.

Figure 6 presents another interesting feature. In this particular locality, the reef possessed four distinct mineralized edges, all of which were mineable. The condition was created by the overlapping of successive reef growths and the development of individual talus zones. In the mining operation, a separate heading was driven on each of the reef edges, leaving the lower grade zones between as pillars. This was a local situation and in most other parts of the mine, single or sometimes double edges were encountered. Any doubt that the reef edges are not the primary mining targets should be dispelled by this example.

The horizontal attitude of the reefs appears to be as important to their ore-controlling ability as the previously discussed vertical variances. Those reefs occurring as rather isolated, uncrowded growths, with open water on all sides at the time of growth, are almost without exception the better mineralized forms. In many instances, the entire reef is mineable. Figure 5 is an example.

In secs. 4 and 9, T. 12 N., R. 9 W., many of the reefs showed a tendency to grow laterally and became complex and overcrowded near the hack reef. Under these circumstances, the better and more continuously mineralized portion of the reef is the fore-reef edge; again, that part of the reef adjacent to the open water.

Some of the larger "overcrowded" reef areas, as mentioned

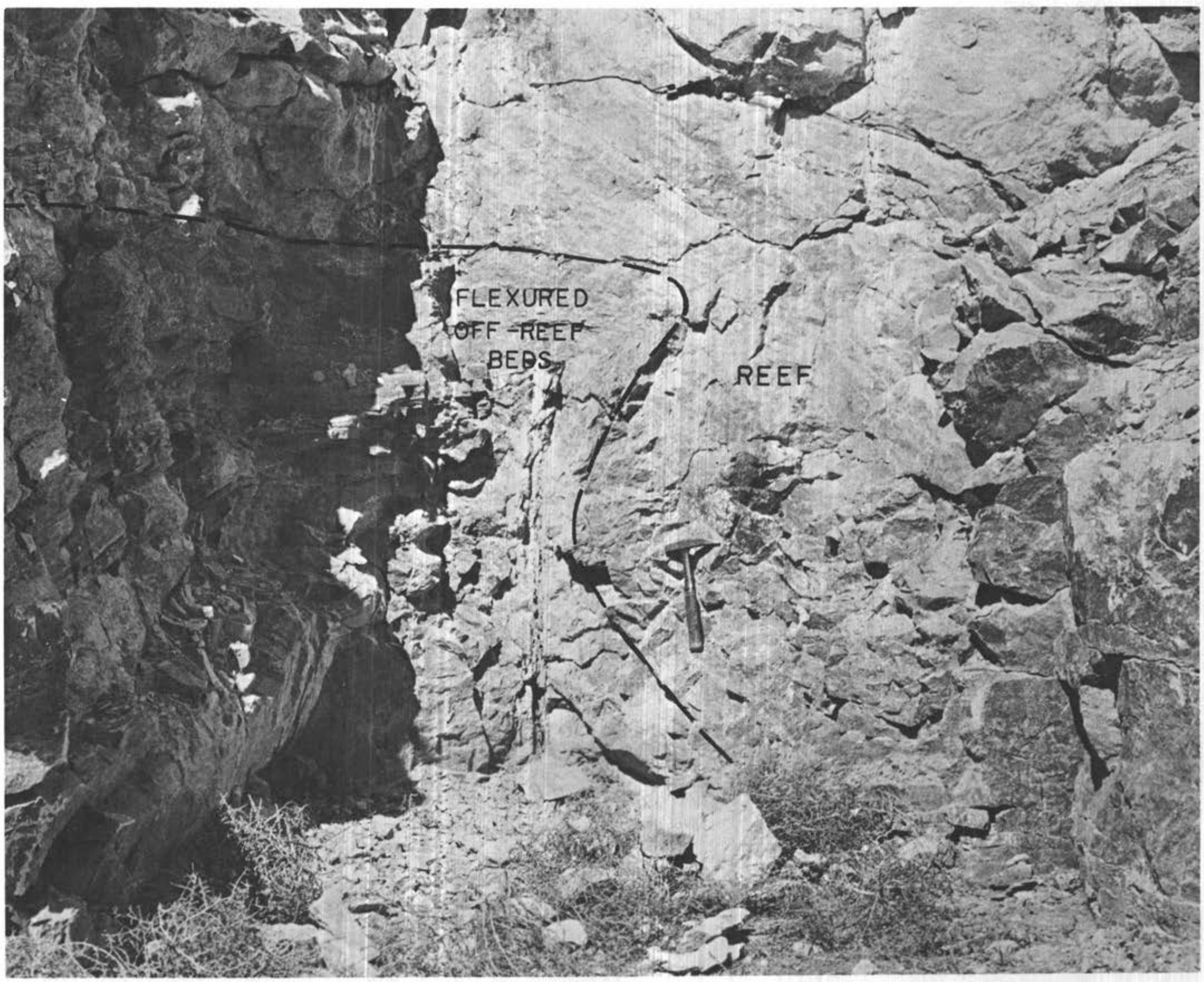


Figure 3

A TYPICAL REEF EDGE IN AN OPEN PIT IN THE NORTH PORTION OF SEC. 9, T. 12 N., R. 9 W.
(Note dashed line along exact edge; right side of photo composed of massive reef facies, left side composed of folded, thin-bedded, fore-reef facies.)

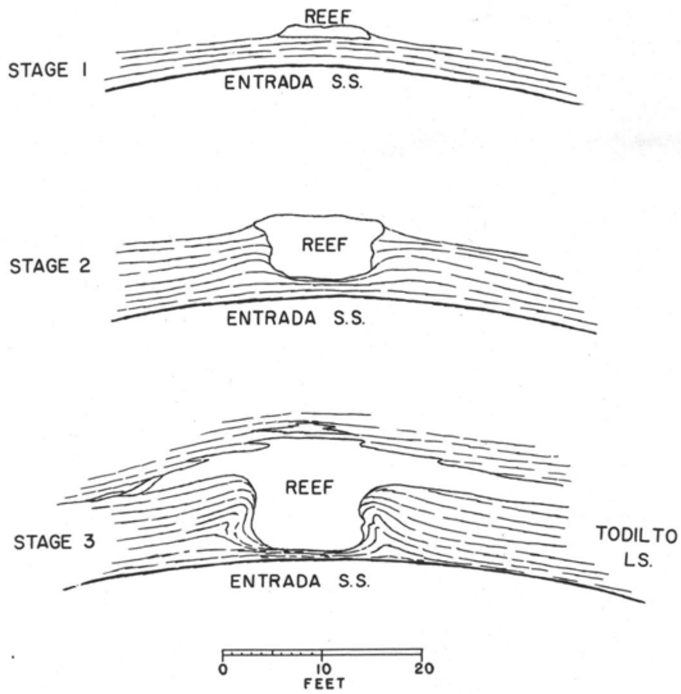


Figure 4

STAGES IN THE DEVELOPMENT OF OFF-REEF FLEXURES

above, developed minor structures which occasionally support mineable ore bodies. Such structures are (1) partly closed lagoons of open water existing within the reef area, (2) long partly isolated "taillike" structures extending from the fore-reef to the back-reef sides in a line generally perpendicular to the fore-reef edge, and (3) faintly defined "V-shaped" channels or valleys within and on the top surface of the reefs.

The above-mentioned partly closed lagoons are normally mineralized at and near the peripheral contact with the reef mass. An excellent example is illustrated in Figure 7. Several open pits in the area are "atoll-shaped," such as the Anaconda Company's "Eyeball" pit (fig. 8), but upon examination they are found to have resulted from the mining of either the periphery of a circular, interreef lagoon or the periphery of an individual, isolated bioherm.

The "taillike" structures mentioned above are not well exposed since they are normally too small to support a mineable heading. Figure 1 illustrates the cross-sectional outline of one of these structures. The horizontal attitude of this type may be inferred from Figure 5. It should be noted that the structures are probably streamlined by the action of local currents.

"V-shaped" channel structures are common in most reefs. In some instances, they are formed by the conjugation of two or more colonies. Channels formed generally perpendicular to the fore reef appear to have served as flumes to accommodate the water which washed over or through the imposed barrier created by the reefs. Many of the structures are well mineralized but seldom exceed one or two feet in width.

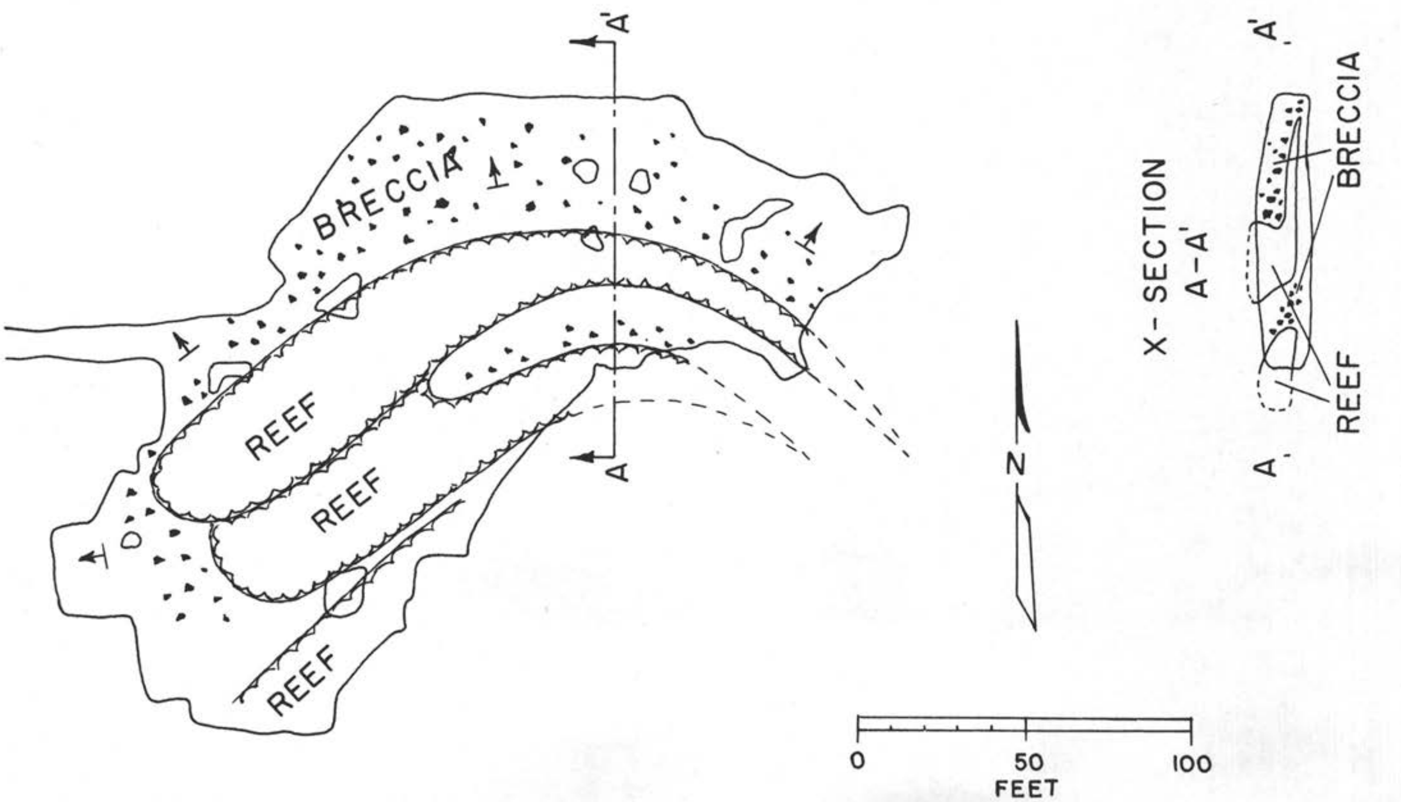


Figure 5

PLAN AND SECTION OF "TWIN" REEF AND STOPE OUTLINE

(This stope is 2000 feet southeast from the main shaft of the Haystack Mountain Development Company, Sec. 25 mine, in N½ sec. 25, T. 13 N., R. 10 W.)

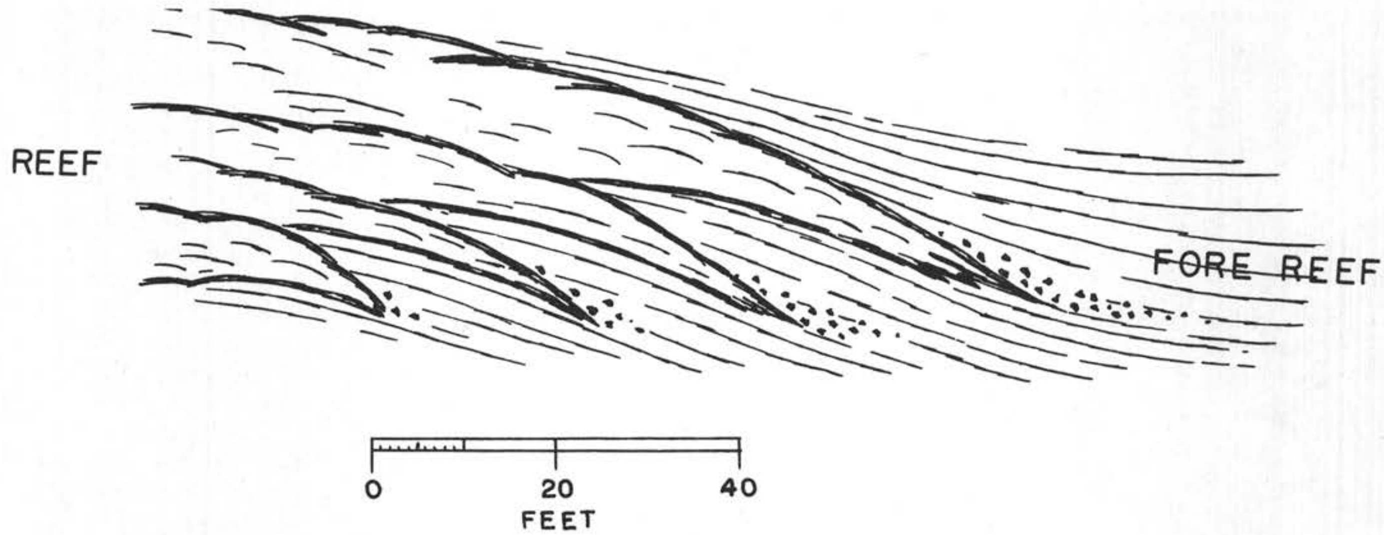


Figure 6

Cross section of complex reef edge
(View north, located 225 feet north of the Rimrock mine main shaft.)

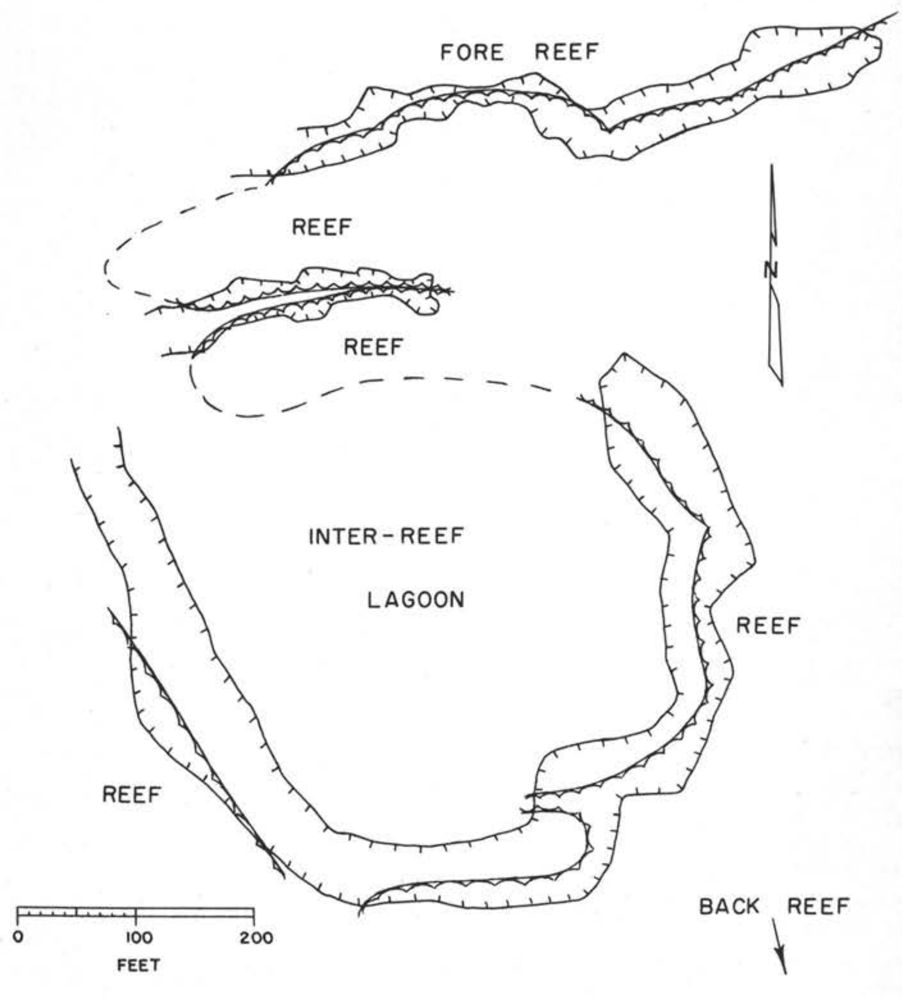


Figure 7

Plan of reef edge around an interreef lagoon
(This reef edge was mined through open pits in the north portion of sec. 9, T. 12 N., R. 9 W. Hachured lines indicate pit outlines.)

Figure 8

"EYEBALL" OPEN PIT IN SEC. 9, T. 12 N., R. 9 W.
(For scale, note tumbleweeds lying in water.)

## CONCLUSIONS

The author has attempted to present facts for the acceptance of the following:

1. The recognition of the existence of reefs and their associated features within the Todilto Limestone.
2. The recognition that the reefs and associated features act as uranium ore-controlling structures.
3. The recognition that certain predictable parts of the ore-controlling structures were more favorable loci for the deposition of primary uranium minerals.

The author is indebted to Lawrence Elkins of the Farris Bros. Mining Co., to A. Day of the Rimrock Mining Co., to Lynn Fuller of the Haystack Mountain Development Co., and to Lloyd Sutton for permitting access to their mines in late 196o and early 1961.

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In August 1961, a request was made to the Grand Junction Operations Office, U.S.A.E.C., for publication and presentation approval of this paper. Appreciation is extended to those persons responsible for the granting of clearance.

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# *Geologic Limitations on the Age of Uranium Deposits in the Laguna District*

ROBERT H. MOENCH

## ABSTRACT

Geologic evidence tentatively dates uranium deposition in the Laguna district to the period between early, near-surface deformation of the Jurassic host rocks and probable early Tertiary tilting in the southeast part of the San Juan Basin. On the basis of crosscutting relations and metamorphic effects, the uranium deposits are clearly older than late Tertiary diabase, faults, and joints. Detailed measurement of the bearing and plunge of a large ore-rod in the Jackpile deposit shows that it is normal to the slightly tilted Dakota Sandstone. On the assumption that such rods were originally vertical, it is inferred that the uranium deposits formed prior to Late Cretaceous or early Tertiary tilting. The close association between uranium deposits and many kinds of structures that formed during or shortly after accumulation of the host sediments indicates that the deposits formed during or after these structures developed.

From all lines of reasoning, it is suggested that the uranium deposits formed in Jurassic time before the host rocks were deeply buried and possibly when they were exposed at the surface. The uranium deposits may have formed where the flow of near-surface ground water was impeded by the stratigraphic and early postdepositional tectonic structures that characterize the mineral belt.

Before the geologic environment of the formation of sandstone-type uranium deposits can be established, work is needed in two areas of geochemical and mineralogic research. Study of the alteration of host sandstones is needed as a clue to the source of elements and the geologic environment in which the elements were extracted, transported, and precipitated. Further study of the association of uranium and carbonaceous matter is needed to establish the humic origin of the carbonaceous matter and to determine whether both were carried and precipitated together.

## INTRODUCTION

Many aspects of the origin of sandstone-type uranium deposits are still enigmatic. This enigma stems partly from the lack of conclusive evidence of the time of uranium deposition relative to the major geologic events that affected the surrounding terrain. For lack of definite geologic evidence to the contrary, the postulated Late Cretaceous or early Tertiary age of ores in the Uravan mineral belt, determined from lead-uranium isotope data (Stieff, Stern, and Milkey, 1953), was almost generally accepted. In spite of the discordant ages obtained from these data (Stieff and Stern, 1956) their studies seem to have had a greater influence on Colorado Plateau uranium geologists than did all geologic observations combined. To geologists so influenced, a Late Cretaceous or early Tertiary age meant that the uranium deposits formed at depths of several thousands of feet. This may be correct, but from other geologic field observations it seems more reasonable that the deposits of the Laguna district are much older and that they formed at shallow depths, perhaps when the host rocks were exposed at the surface.

This paper summarizes the evidence that bears on the age of uranium deposits of the Laguna district—about 45 miles west of Albuquerque—speculates on their origin, and outlines some critical problems that require further study. Determination of absolute age is not the end in itself; rather, it is an important link in a chain of data that includes the age of uranium deposition relative to fracturing, igneous activity, tilting, and sedimentation and deformation of the host rocks. Absolute ages from isotopic data for uranium deposits along the southern margin of the San Juan Basin have not been published. The geologic evidence, though inconclusive, does suggest that uranium deposition in the region was more closely allied to the early postdepositional history of the host rocks than is commonly supposed.

This paper is based on the results of areal and mine mapping that was done by the writer and associates, J. S. Schlee and W. P. Puffett, from 1955 through 1958. The work was done on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

## GEOLOGY

The Laguna district is underlain by an exposed sequence of sedimentary strata that ranges in age from Triassic to Late Cretaceous. In ascending order, these are the Chinle Formation of Late Triassic age; the Entrada Sandstone, Todilto Formation, Summerville Formation, Bluff Sandstone, and Morrison Formation, all of Late Jurassic age; the Dakota Sandstone of Early and Late Cretaceous age; and the intertonguing strata of the Mancos Shale and Mesaverde Group of Late Cretaceous age. The oldest rocks are exposed in the southern part of the district (fig. ). The exposed column totals about 380o feet in thickness, including about 1300 feet of Jurassic strata. Before deep erosion began in Tertiary time, the Jurassic rocks were buried by possibly a mile of Cretaceous rocks and an additional unknown thickness of early Tertiary rocks.

The uranium deposits are restricted to two zones within the sequence of Jurassic strata (Hilpert and Moench, 196o, p. 431-437) : (1) the Entrada Sandstone and limestone of the Todilto Formation and (2) sandstones of the Morrison Formation. The Todilto Formation is divisible into two units: limestone from 2 to 35 feet thick and overlying lenticular masses of gypsum-anhydrite as much as 6o feet thick. The Morrison Formation, as much as 600 feet thick, is divisible into four units, in ascending order: the Recapture Member, Westwater Canyon Member, Brushy Basin Member, and the Jackpile sandstone of local usage (Schlee and Moench, 1961).

Exposed igneous rocks, of late Tertiary to Quaternary age, include many diabase sills and dikes, basalt plugs, and a succession of basalt flows that cap eroded pediments at several levels above the drainage. These rocks constitute part of the Mount Taylor volcanic field, most of which lies to the northwest of the district (Hunt, 1938). The oldest flows cap the so-called Ortiz high-level erosion surface, which may be as young as early Pleistocene (Bryan and McCann, 1938, p. I I; Wright, 1946, p. 435-444).

The district is in the southeastern corner of the San Juan Basin of the Colorado Plateau. As shown by the structure contours in Figure 1, the Cretaceous strata in the vicinity of the major uranium deposits dip gently northwest into the

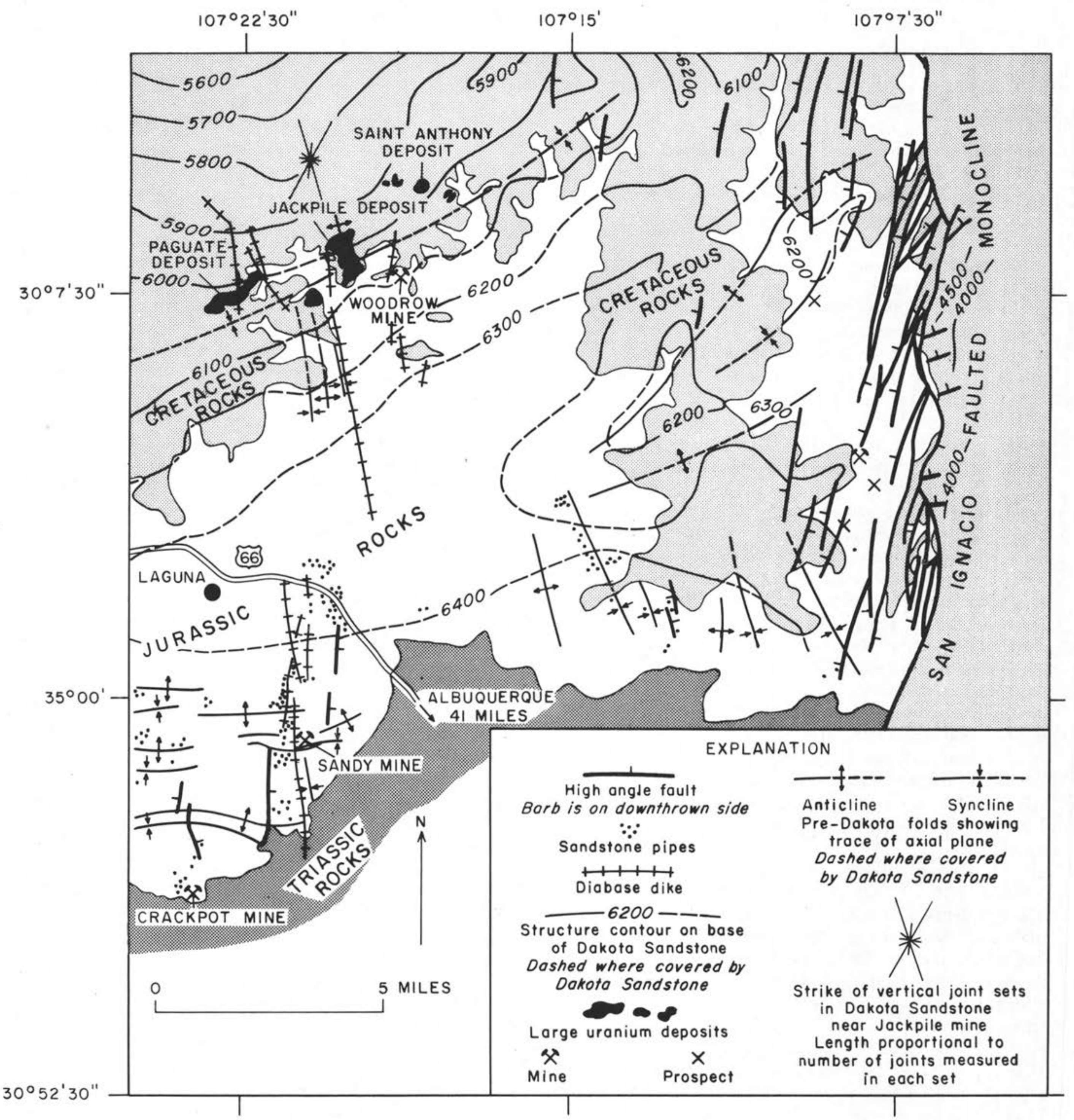


Figure 1

GENERALIZED GEOLOGIC MAP OF THE LAGUNA DISTRICT SHOWING DISTRIBUTION OF URANIUM DEPOSITS basin. The north-trending San Ignacio faulted monocline (fig. 1) marks the boundary between the plateau and the Rio Grande depression to the east. Although dips exceeding two degrees are exceptional in most of the district, three general periods of tectonic activity are recognized: ( ) gentle folding in Jurassic time, (2) regional tilting and gentle folding in Late Cretaceous to early Tertiary time, and (3) regional jointing, faulting, and igneous activity in later Tertiary and possibly Quaternary time.

The Jurassic deformation produced two sets of folds of low amplitude, one trending east to northeast, the other trending north-northwest (fig. i ). These folds are known to predate the Early Cretaceous Dakota sedimentation because folded Jurassic rocks are unconformably overlain by less-deformed beds of the Dakota. Jurassic folding was accompanied by lateral flowage of unconsolidated limestone of the Todilto Formation into the synclines, producing the variety of intraformational flowage folds that are characteristic of that unit and accounting for the thickening of limestone in the synclines. Folding was also accompanied by slumping and internal faulting of unconsolidated elastic sediments and by the formation of peculiar cylindrical subsidence structures or sandstone pipes (Hilpert and Moench, p. 437-443). Folding also markedly influenced sedimentation. The fluvial Jackpile sandstone, for example, seems to have accumulated in a broad, east- to northeast-trending syncline that deepened and expanded during sedimentation (Schlee and Moench, p. [1]47150).

Regional Late Cretaceous or early Tertiary tilting and gentle folding are not datable by evidence obtained within the district, but very likely were more or less contemporaneous with datable tilting in other parts of the San Juan Basin. On the northern end of the Nacimiento uplift, vertical to overturned strata of Paleocene and older age are overstepped by beds of Eocene age, which in turn dip basinward as much as 4o degrees (Kelley, 1955, p. 85). On the north flank of the San Juan Basin, the upper part of the Animas Formation (Upper Cretaceous and Paleocene) unconformably overlies the McDermott Member of the Animas Formation and older strata, indicating basinward tilting of that flank in Late Cretaceous or early Tertiary time (Hunt, 1956, p. 57).

The third and youngest deformation probably reached a climax during rapid subsidence and sedimentation in the nearby Rio Grande depression in late Tertiary time. In the district, this deformation produced the north-trending normal faults, the San Ignacio faulted monocline (fig. 1), and most of the joints in the sedimentary rocks. The joint diagram shown in Figure 1 is highly characteristic for the entire district and is similar in many respects to the joint pattern of the Lucero uplift (Duschatko, 1953). The third deformation was accompanied by the emplacement of an interconnecting system of diabase sills and dikes, for dikes occupy characteristic joints of the fracture system and sills are cut by joints and faults of the same fracture system.

## URANIUM DEPOSITS

The Laguna district forms the southeastern end of the Grants mineral belt, which extends southeastward about 8o miles from Gallup to Laguna (Hilpert and Moench, fig. 2). Hilpert and Moench summarized it as follows (p. 462):

> . . . the belt[1] parallels a number of controlling and definitive geologic features. In addition to the Jurassic highland and the southern limits of the Todilto limestone and the Morrison formation, it parallels the easterly trend of the major Jurassic folds, the dominant orientation of the intraformational folds in the Todilto limestone, the elongation of the thickest parts of the host sandstones of the Morrison formation, the dominant known sedimentary trends within these host sandstones, and, finally, it parallels the individual belts of deposits. . . .

In the Laguna district, the largest deposits by far are in the Jackpile sandstone of local usage. Anaconda's Jackpile open-pit mine, for several years one of the world's largest producers of uranium, works a multimillion-ton deposit in the Jackpile sandstone. Many smaller deposits, containing a few tons to a few thousand tons, are also present in the stratigraphically lower units, the Westwater Canyon Member of the Morrison Formation, the limestone of the Todilto Formation, and the Entrada Sandstone.

The large uranium deposits in the Jackpile sandstone are composed of one or more semitabular ore layers. In plan view they range from nearly equant to strongly elongate. Viewed in section (fig. 2), the layers are figuratively suspended within the host sandstone; only locally do they border directly on prominent mudstone beds, diastems, or formation contacts. The Jackpile deposit, the largest in the district, is several thousand feet long and averages about 2000 feet wide; individual ore layers rarely exceed 15 feet in thickness, but several "stacked" layers may aggregate 5o feet in thickness.

The dominant ore minerals of the relatively unoxidized parts of deposits are coffinite and uraninite. These minerals are intimately mixed with carbonaceous matter, which is particularly abundant in deposits in the Morrison Formation. This mixture coats sand grains and locally impregnates the sandstone and embays its constituents. Other minerals associated with ore are vanadium clay, pyrite, and other sulfides (Moench, 1962a).

Although the origin of uraniferous carbonaceous matter is still a subject of controversy, available infrared and chemical data (I. A. Breger, written communications, 1959, 5960) favor an origin from decaying vegetable matter. Granger et al. (1961 ) summarized the known properties of carbonaceous matter in Ambrosia Lake ores, and likewise favor a vegetal origin.

Where oxidized, the ores contain a variety of minerals of high-valent uranium and vanadium. These minerals occupy pore spaces, line fractures, and coat relatively old mine walls.

## RELATION OF DEPOSITS TO GEOLOGIC STRUCTURES

As described by Hilpert and Moench (p. 449), the uranium deposits of the Laguna district have been localized by various sedimentary and geologic structures. In addition, the deposits are crossed by fractures and diabase sills, or dikes, and seem to have been tilted. These relationships provide a basis for restricting the time during which uranium deposition originally took place.

1. This is the "southern San Juan Basin mineral belt," for which "Grants mineral belt" is substituted in this memoir. *VCK*

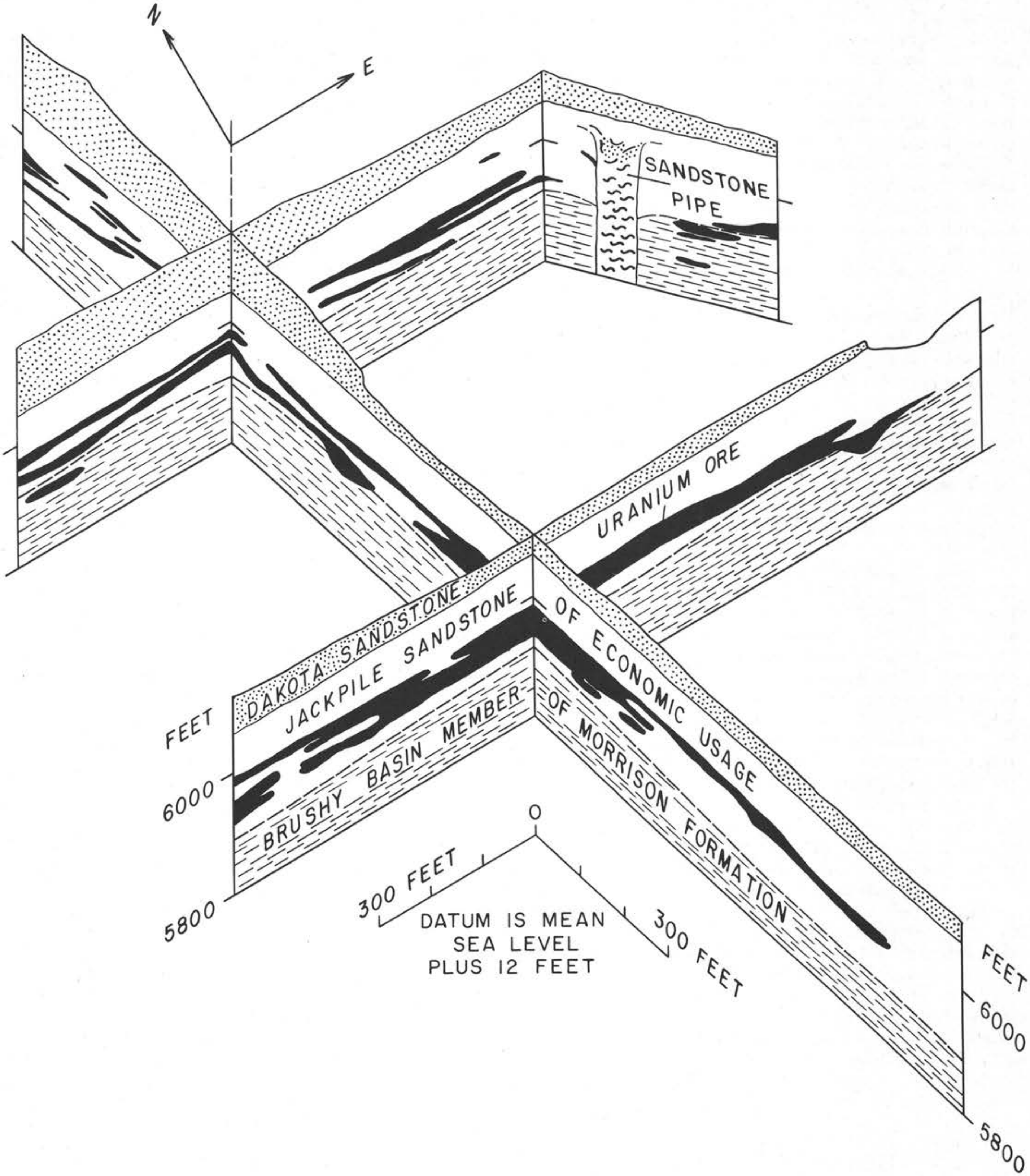


Figure 2

GENERALIZED FENCE DIAGRAM OF SOUTHEASTERN SIDE OF JACKPILE DEPOSIT

## LATE TERTIARY DIABASE, FAULTS, AND JOINTS

The uranium deposits are clearly older than the diabase sills and dikes, and show no obvious relation to faults and joints. Deposits in the Jackpile and Sandy mines are cut and displaced by diabase (fig. 3). In addition, uranium deposits of the Sandy mine have been metamorphosed near contacts with relatively thick sills, producing a vanadium-rich garnet (Moench, 1962b). Although the Jackpile deposit is about parallel to one prominent joint set in the nearby rocks, it is not parallel to the other important sets and the nearby fault (fig. 1). Further, groups of deposits, as the Paguate—Jackpile—St. Anthony group and a group of many small deposits in the Sandy mine, show no linear relation to fracture patterns. Joints of the important late Tertiary sets locally contain scattered minerals of hexavalent uranium that apparently formed during oxidation of black ore. Unlike some intraformational Jurassic faults, late Tertiary joints have not localized black ore.

Uranium in chill borders of diabase dikes (locally ore grade) in the Jackpile mine postdates the diabase, but evidently it was redistributed from the pre-existing Jackpile deposit. The diabase is uraniferous only where it cuts ore. Microscopic examination shows that its uranium is contained in uranophane, a hydrous calcium uranyl silicate, that fills longitudinal fractures in the chill borders. These fractures probably formed as the diabase cooled and were filled with uranophane either as they formed or at a much later time.

The relations among joints, faults, and ore in the Laguna district are consistent with those described by Granger et al. (p.1188-1191) for the Ambrosia Lake area of the Grants district but are less complicated. Stratigraphically controlled prefaulting unoxidized ores in the Ambrosia Lake area are distinguishable from postfaulting unoxidized ores that tend to parallel the strike of faults, and are thought to have formed by redistribution of prefaulting ores. Unoxidized postfaulting ores have not been recognized in the Laguna district.

## LATE CRETACEOUS TO EARLY TERTIARY TILTING

The uranium deposits of the district apparently formed prior to tilting at the southeast corner of the San Juan Basin. This relative dating is based on the angular relations between near-vertical ore rods in the Jackpile mine and the tilted host

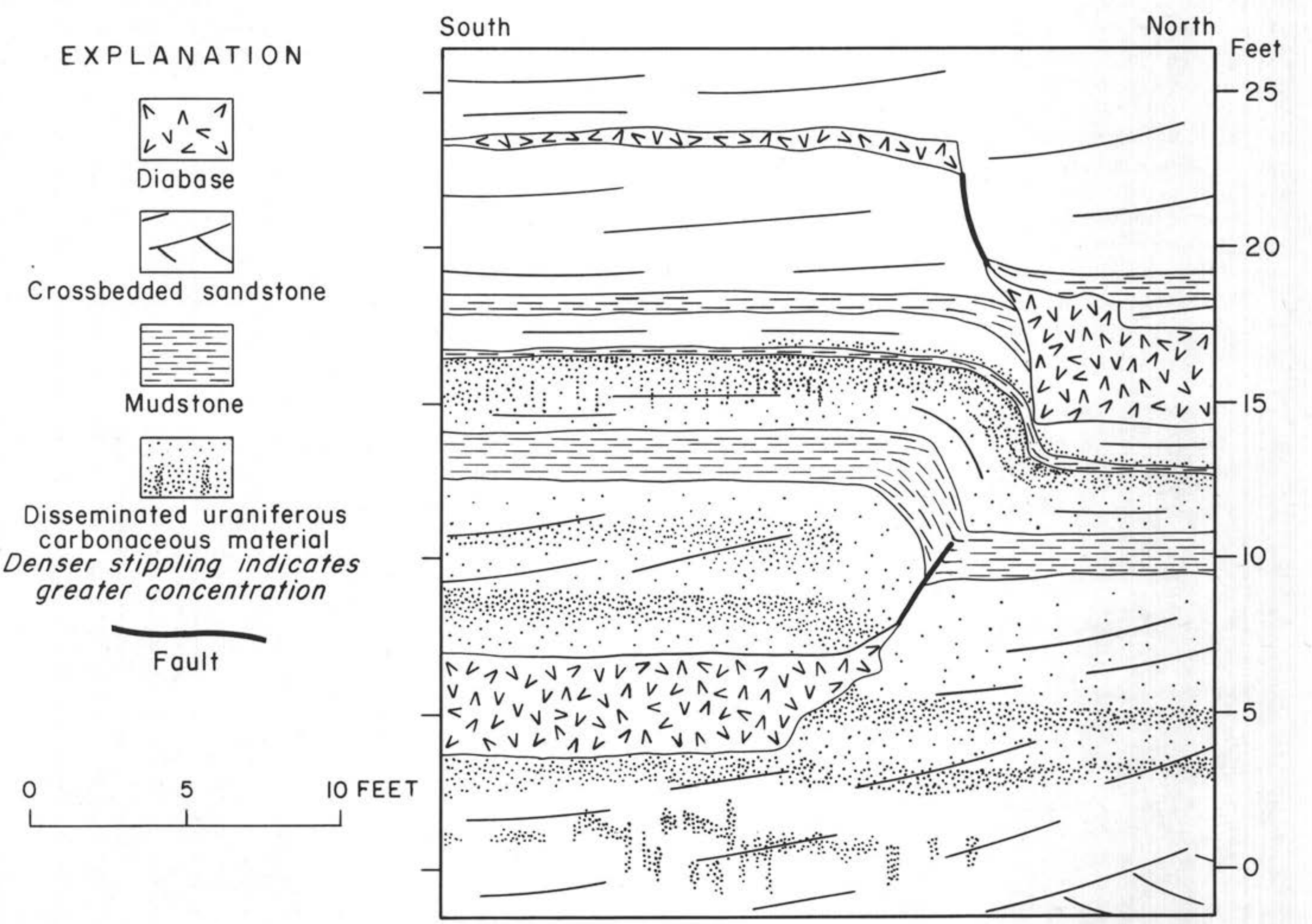


Figure 3

Field sketch showing deformed host rocks and uranium ore where intruded by diabase, Jackpile mine rocks. On the assumption that ore rods formed by downward flow of carbonaceous matter under the influence of gravity, it was thought that an accurate determination of the bearing and plunge of rods would provide a basis for determining the age of the uranium deposits relative to tilting. If the rods are vertical, the deposits probably postdate the tilting; if the rods are normal to the strike and dip of the host rocks, the deposits probably predate the tilting.

Ore rods are common in the Jackpile and St. Anthony deposits. They are composed of uraniferous carbonaceous matter which coats sand grains and, locally, thoroughly impregnates sandstone. Like other forms assumed by ore, they cut across bedding. Typical rods *(see* Hilpert and Moench, fig. 12) are several inches high and an inch in diameter; some are much smaller; rods as large as four feet high and four inches wide near the base have been found. They range in shape from thin, pencillike cylinders to rather broad-based cones. At places these shapes are simple and nearly perfectly formed; more commonly they are complicated by internal mottling and irregular borders (fig. 4). Characteristically, the cone-shaped rods broaden downward. At the top of a cone, carbonaceous matter may thoroughly impregnate the rock; downward, it becomes more diffuse.

These characteristics suggest that the rods formed by downward flow of fluid carbonaceous matter in unsaturated sandstone or in sandstone saturated with immobile water. Possibly, humic compounds carried in solution by ground water were precipitated as rather gelatinous concretions that subsequently flowed downward and gradually dispersed laterally as they flowed. Downward flow could have taken place if the specific gravity of the carbonaceous fluid had been greater, perhaps due to uranium content, than that of the surrounding immobile ground water or if the water table had dropped below the site of precipitation. In either situation the resulting rod would be vertical.

One rod that was suitably tall for an accurate measurement of bearing and plunge was partly excavated so that a plumb bob could be hung from its apex to its approximate base (figs. 5 and 6). The rod is more than 43 inches high. At its apex, it is about half an inch in diameter; here uraniferous carbonaceous matter thoroughly impregnates the sandstone. The rod broadens and becomes more diffuse downward, so that its center line could be determined accurately only to a depth of about 18 inches. The plane of the rod and plumb line (fig. 5A) strikes within 1 o degrees of the dip direction of the Dakota Sandstone, determined in the mine area by plane table readings on a thin but extensive black shale bed within the unit. The rod and plumb line converge downard (fig. 5B). As shown in Figure 6, the upper 18 inches of the rod is normal to the Dakota Sandstone; the lower part of the rod, where measurements are less accurate, plunges at a slightly lower angle.

From the foregoing evidence, the Jackpile deposit is inferred to have been tilted in Late Cretaceous to early Tertiary time. The fact that the main Jackpile ore layers conform to the gentle northwesterly dip of the Dakota Sandstone is consistent with this interpretation. If the deposit formed during or after tilting, it might be expected to be more nearly horizontal than the stratification as, for example, at the Sandy mine.

Admittedly much uncertainty is involved in the foregoing. The exact age of the tilting of the margin of the San Juan Basin in the Laguna region has not been established; the origin of ore rods is not well understood; and one reading of bearing and plunge might be contradicted by others. It is hoped, however, that similar measurements will be made wherever rods are found.

## PRE-DAKOTA FOLDS AND INTRAFORMATIONAL STRUCTURES

The close association between uranium deposits and many varied intraformational structures indicates that the deposits formed either during or after these structures developed. As stated, such structures as folds in limestone of the Todilto Formation, intraformational faults in sandstone, and sandstone pipes all formed during or shortly after the accumula-

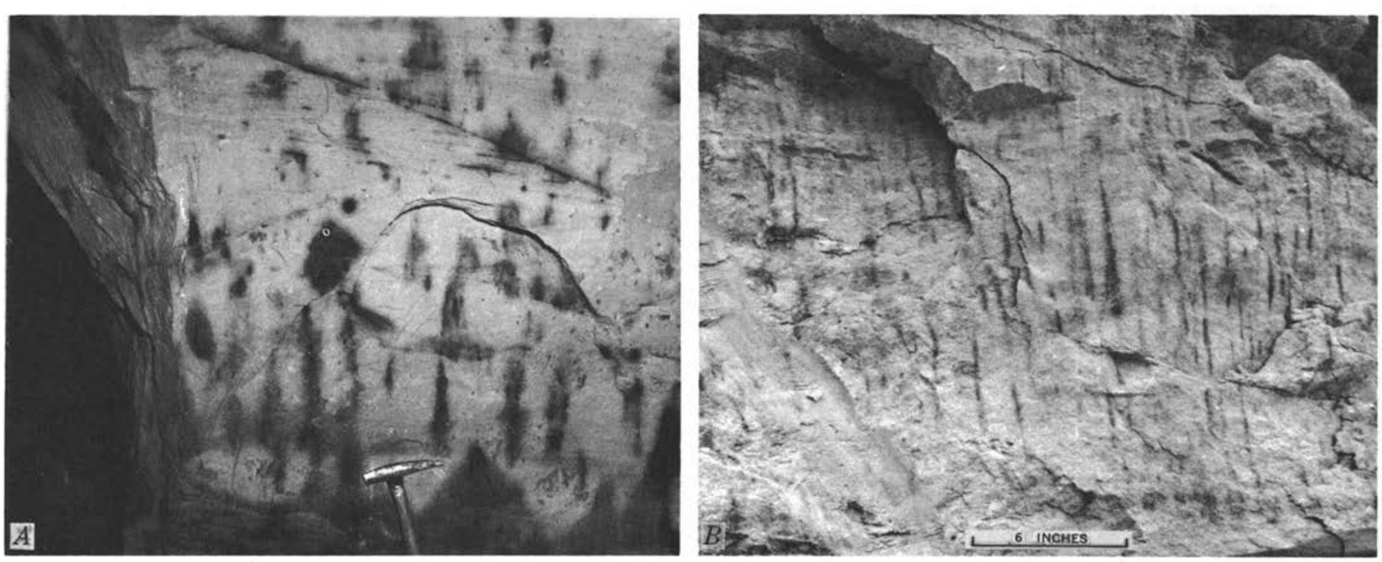


Figure 4

Photographs of ore rods. A, St. Anthony mine; B, Jackpile mine tion of the sediments that contain them. Some of the larger pre-Dakota folds also developed as Jurassic sediments accumulated.

The spatial association between uranium deposits and intraformational folds in limestone of the Todilto Formation is well known. Examples in the Ambrosia Lake area and Laguna district were illustrated by Hilpert and Moench (figs. 17, 18). The shapes of such uranium deposits are governed by the character of the folds that contain them. Deposits associated with long, narrow folds that have steep to overturned limbs are stringlike or pencillike. A deposit may occupy the central part of an anticline, or a syncline between two prominent anticlines. Deposits associated with doubly plunging anticlines or domes that have gently dipping limbs are elliptical or equant in plan and roughly lenticular in section. The Crackpot deposit in the southern part of the district (fig.1), for example, is about loo feet long, 85 feet wide, and as much as 12 feet thick where it contains more than o. i percent $U_3O_8$. Viewed in section, it is constricted just below the contact between the massive and bedded units of the limestone.

The Woodrow mine is a famous example of a uranium deposit in a sandstone pipe (Hilpert and Moench, p. 456-457). Because the top of this pipe has been removed by erosion and the bottom has not been reached by mining or drilling, its origin is controversial. Very likely, however, the Woodrow pipe is similar to hundreds of others in the district that clearly formed during accumulation of the surrounding sediments. The top of one pipe in the Jackpile mine was exposed by mining (fig. 2; Hilpert and Moench, fig. 8). This pipe formed during deposition of the Jackpile sandstone and was buried by additional Jackpile sandstone. A small amount of black ore has been found along the boundary ring fault. Near its top, the pipe contains abundant nonuraniferous, low-rank coal fragments.

In contrast with the ubiquitous post-Dakota joints, the few intraformational fractures seen in the Jackpile ore body have localized uraniferous carbonaceous matter. The small, high-angle thrust fault that cuts the mudstone bed shown in Figure 7 seems to have formed in part during accumulation of the mudstone bed and in part afterward. It is truncated at its top by a lower angle fault, which in turn is truncated by overlying cross-bedded sandstone. Uraniferous carbonaceous matter impregnates sandstone along the footwall of the high-angle fault.

Relatively large pre-Dakota folds seem to have localized uranium deposits. In the Sandy mine, many small deposits in the Entrada Sandstone and limestone of the Todilto Formation are localized along the crest and steep, southeast-facing limb of a northeast-trending fold. This limb is about 1300 feet broad from crest to trough and has a structural relief of about Too feet. As shown in section by Hilpert and Moench (fig.15), uranium deposits in the structurally high areas are largely in the Entrada Sandstone, whereas deposits in the structurally low areas are in the limestone. This suggests that

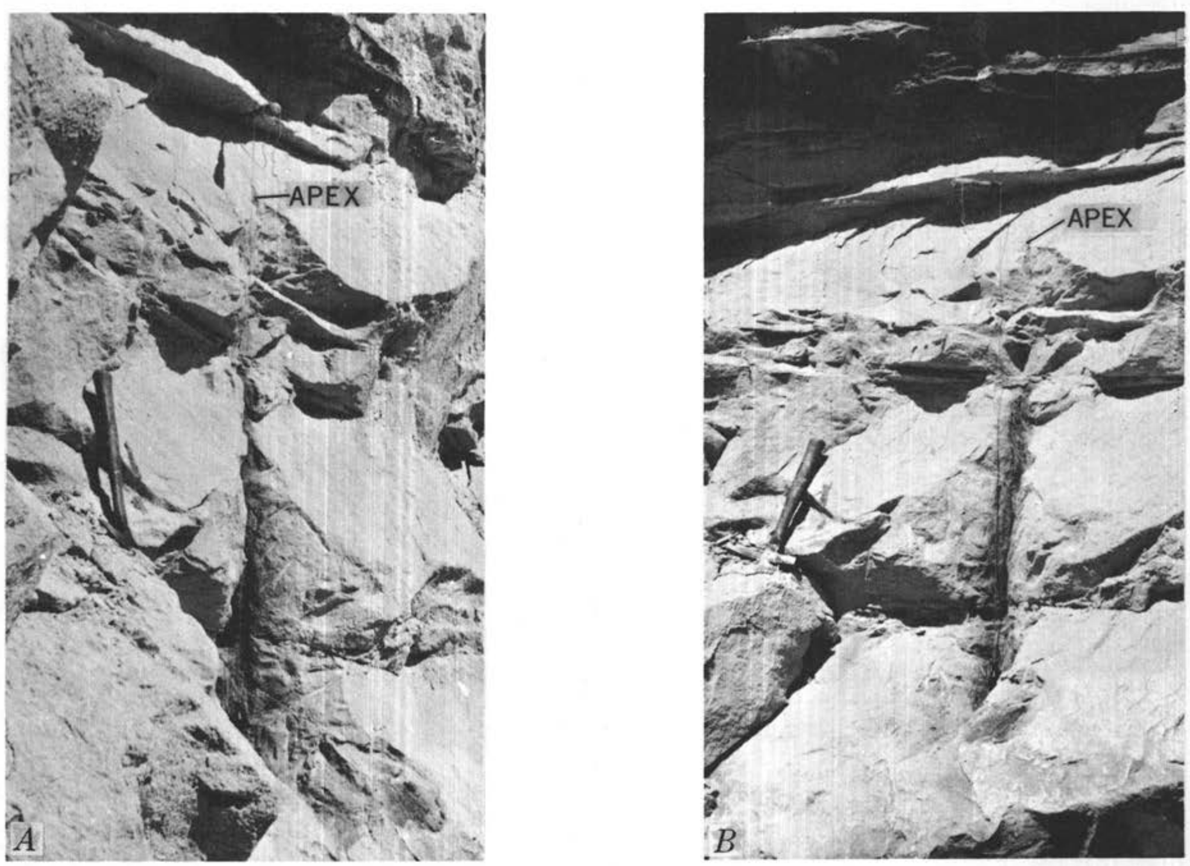


Figure 5

PHOTOGRAPHS OF EXCAVATED ORE ROD, JACKPILE MINE. A VIEWED PARALLEL TO DIP DIRECTION OF DAKOTA SANDSTONE; B, VIEWED PARALLEL TO STRIKE OF DAKOTA SANDSTONE the deposits formed during or after folding, above or below some sort of subhorizontal, gravity-controlled fluid interface that crossed the formational contact. The fact that the group of deposits is tilted toward the syncline, though less so than the host rocks, suggests that uranium deposition accompanied folding. Probably folding shortly followed accumulation of the limestone, because the limestone is markedly thicker in the trough, largely because of gravitational flowage of unconsolidated limestone.

A broad, post-Jackpile, pre-Dakota anticline may have had some controlling influence on the Jackpile deposit. The Jackpile deposit is elongate north-northwest, about at right angles to other major deposits in the same northeast-trending zone. A pre-Dakota arch of low amplitude has been recognized in the Jackpile open pit (Hilpert and Moench, fig. 9). Although the trend of the arch cannot be determined from outcrops, isopachs of Jackpile sandstone determined from drill data (furnished by the Anaconda Company) are strongly elongate north-northwest in the northern half of the ore body. The data show that relatively thin Jackpile sandstone represents

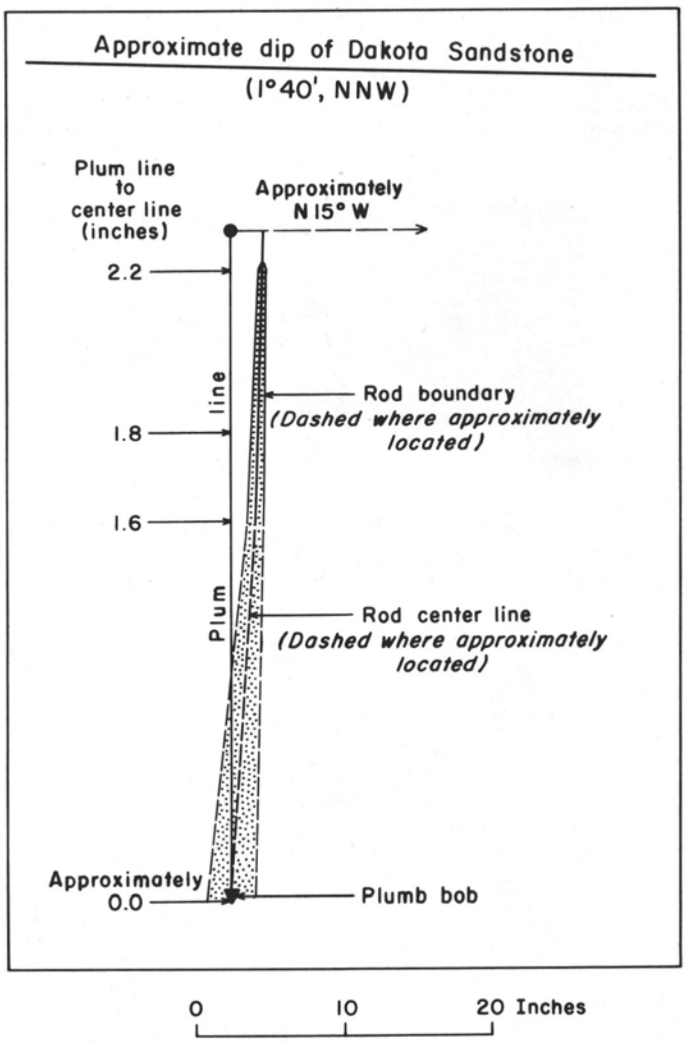


Figure 6

FIELD SKETCH OF EXCAVATED ORE ROD, JACKPILE MINE, SHOWING DOWNWARD CONVERGENCE WITH PLUMB LINE

the north-northwest-trending anticline. Isopachs of the southern part of the Jackpile deposit, seem to reflect intersecting north-northwest-trending folds and east-trending channellike structures.

## ORIGIN

Evidence presented seems to indicate that uranium deposition occurred sometime during the period between the development of pre-Dakota structures and the Late Cretaceous to early Tertiary tilting. Within this interval, all deposits could have formed at the same time or at widely separate times. They could have formed during or shortly after the accumulation of the sediments that contain them or much later after deep burial.

The opinion that the uranium deposits of the district formed in Jurassic time shortly after the accumulation of the host rocks, and perhaps when these rocks were exposed at the surface, is favored in this paper. At that time a broad, westnorthwest-trending highland (McKee et al., 1956) existed a short distance to the south of the Grants mineral belt and was probably the major source of sediments within the belt. Surface and ground waters, of the type outlined by Hostetler and Carrels (1962), flowing from the highland could have extracted uranium and vanadium from the rocks and transported them to the sites of deposition. Such waters could also have extracted soluble humic compounds from surficial or buried decaying plant debris (Vine, Swanson, and Bell, 1958). These substances could then have been precipitated together where the flow became impeded by the prominent strati-graphic and pre-Dakota tectonic structures that characterize the mineral belt. Presumably, impedance of flow would induce chemical changes in the ore-bearing ground water and reduce its capacity to carry uranium, vanadium, and perhaps humic compounds.

In areas of impeded ground-water flow, for example, the reduction of sulfate by anaerobic bacteria (Jensen, Field, and Nakai, 196o) might be accelerated. The hydrogen sulfide thus generated might effect a reduction and precipitation of uranium (Jensen, 1958). In addition, weak acidification of the ground water by hydrogen sulfide might also cause precipitation of humic compounds, which in turn would tend to extract uranium from solution (Vine, Swanson, and Bell). The same processes could apply to deposits in the Entrada Sandstone and limestone of the Todilto Formation, with the exception that soluble humic compounds were in much reduced supply.

Many of the deposits of the district may have formed below a water table. Though a water table would not account for the upper contacts of ore bodies, which tend to be rather irregular, it might account for peculiarities in the distribution of uranium deposits and of unmineralized carbonaceous materials. The Jackpile deposit contains several ore layers that are suspended within the sandstone. At a level well above the main ore layer in the southern part of the mine, a sandstone pipe (fig. 2) contains abundant, unmineralized, low-rank coal fragments. As some low-rank coal is capable of extracting much uranium from an aqueous solution (Moore, 1954), very likely this coal would have been mineralized if uranium-bearing solutions had ever come in contact with it. Possibly during mineralization a water table extended below the coal and above the main ore body. Likewise, the distribution of uranium deposits in the Sandy mine might be explained by postulating formation of the deposits below a water table that crossed the gently folded Entrada—Todilto contact, which evidently was gently folded shortly after Todilto sedimentation. Fischer, Haff, and Rominger (1947), Marks (1958), and Woodmansee (1958) recognize the possible important role of water tables in the localization of vanadium and uranium deposits in the Colorado Plateau and in Wyoming.

Of many possible subjects of future research, two seem to be outstanding: the source of uranium, vanadium, and other elements and, second, the nature of the association between uranium and carbonaceous matter.

A logical source of elements is the sedimentary rocks of the region, for the uranium deposits of the district are in or are closely associated with extensive alteration zones. The upper part of the Entrada Sandstone, for example, is a possible source of elements in the deposits of the Entrada Sandstone and Todilto Limestone; it is characteristically nearly white, whereas the lower part is red or light brown. Field and petrographic studies show that the white part is an alteration zone that formed at the expense of the red. Preliminary chemical analyses suggest that vanadium and possibly uranium might well have been extracted from the Entrada during bleaching. The Jackpile and other Jurassic sandstone units have been kaolinized where directly overlain by the Dakota Sandstone. This alteration is evidently the result of extensive weathering prior to Dakota deposition (Schlee and Moench; Leopold, 1943). A detailed field, petrographic, and chemical study of this alteration is needed to determine whether the sandstones were likely sources of elements, and whether the alteration and extraction of elements was a weathering process. Expo sures of the critical units in the Laguna region and to the south are suitable for such study.

The nature of the association between uranium and carbonaceous matter is unknown. The humic origin of the carbonaceous matter, though likeliest, has not been established satisfactorily. Further, it is not known whether the carbonaceous matter and uranium were carried by the same solution and precipitated together or whether the carbonaceous matter was precipitated first and extracted uranium from solution at a later time. Viewed under the reflecting microscope at high magnifications and in oil immersion, high-grade concentrations of uraniferous carbonaceous matter show peculiar blebby and vein textures. The chemical, mineralogical, and structural nature of these peculiar textures has not been determined or interpreted.

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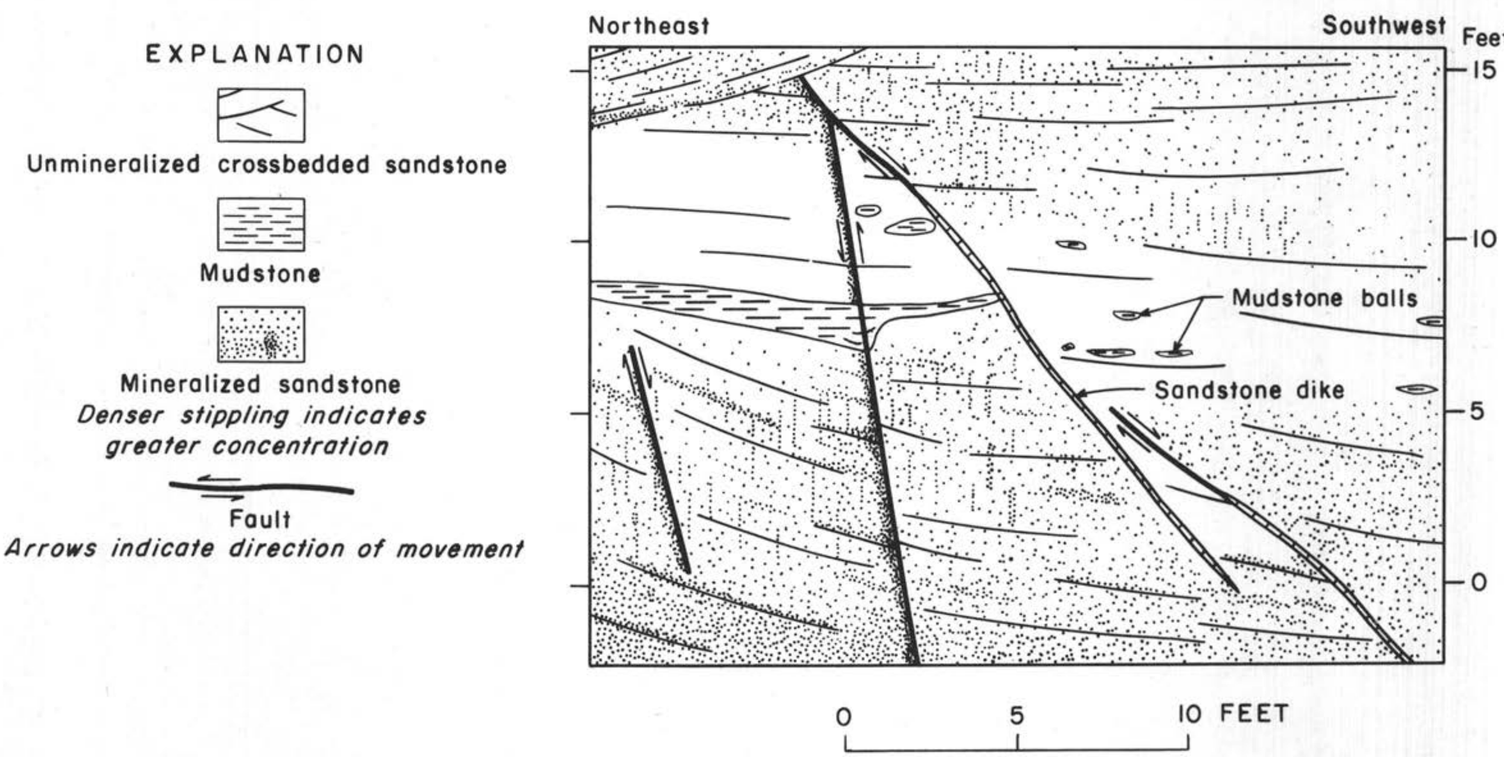


Figure 7

FIELD SKETCH SHOWING CONCENTRATION OF URANIFEROUS CARBONACEOUS MATTER ALONG INTRAFORMATIONAL FAULT, JACKPILE MINE

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# *Geology of the Jackpile Mine Area*

DALE F. KITTEL

## INTRODUCTION

The Jackpile uranium deposit is about eight miles north of Laguna, a village on U.S. Highway 66. For purposes of this paper, the Jackpile mine area includes about 3o square miles in which are located the Jackpile, Paguate, Woodrow, St. Anthony, and L-Bar uranium deposits shown in Figure 1. The first three deposits named have been mined to varying degrees by The Anaconda Company, which holds long-term mining leases on the Laguna Indian Reservation and on parts of the L-Bar Cattle Company's holdings. The St. Anthony deposit has been mined underground by the Climax Uranium Corporation.

Discovery of the Jackpile deposit was made on November 8, 1951, when radioactivity from the outcrop of the southern part was detected by airborne scintillation equipment. Subsequent exploration and development work outlined the ore body to its presently known size. The Jackpile deposit is not being mined at this time because current uranium economics favor production from the nearby Paguate deposit.

The Paguate deposit, which does not crop out, was discovered by core drilling in June 1956. Subsequent development drilling in the deposit indicates that related trends of mineralization crop out south of the ore body, where the Paguate road crosses a Dakota sandstone—Jackpile sandstone rim.

Since the discovery of the Jackpile deposit, about 1,440,000 feet of cored and noncored holes have been drilled in and around it and the Paguate deposit, and it is estimated that an additional 160,000 feet of similar drilling has been done in and around the L-Bar and St. Anthony deposits.

As of the beginning of 1963, about 6.5 million tons of ore containing about 28 million pounds of $U_30_8$ have been removed from the Jackpile and Paguate deposits; mining of this ore has necessitated the removal of about 76.6 million tons of overlying and associated waste and low-grade material.

Most of the geological information presented in this paper has been obtained from the surface geological work and exploration drilling that has constituted the main effort of Anaconda's uranium exploration program in the area.

## STRATIGRAPHY

Figure 2 is a stratigraphic column of sedimentary beds in the Jackpile area. Beds below the Morrison Formation are not exposed in the immediate Jackpile area, but a cored hole in the south end of Jackpile mine was collared in Dakota Sandstone and bottomed in Entrada Sandstone after penetrating 605 feet of Morrison sediments, 276 feet of Bluff Sandstone, 120 feet of Summerville Formation, 74 feet of Todilto anhydrite, and 10 feet of Todilto limestone.

Prior to 1954, it was thought that the Morrison Formation in the Jackpile area consisted of only the Recapture Claystone Member and the overlying Westwater Canyon Sandstone Member, but inconsistencies in the nomenclature, as noted by Freeman and Hilpert (1957), resulted in revision by the U.S. Geological Survey so that four units are now general recognized as constituent members of the Morrison Formation.

The lowermost of these units, the Recapture Member, is 5o to 100 feet thick in the Jackpile area. It conformably overlies the Bluff Formation and consists mainly of sandy claystone that varies in color from green to maroon. Interbedded with the claystone are lenses of sandstone that often make difficult the delineation between Recapture sandstone and Bluff sandstone recovered in drill cores. This difficulty is normally resolved by the use of gamma-ray probing equipment because the contact between the two formations is usually well defined on the resultant hole logs.

Overlying the Recapture Member is a discontinuous sandstone bed up to 5o feet thick which Freeman. and Hilpert assign to the Westwater Canyon Member of the Morrison Formation. It is a typical Morrison sandstone for the most part, as it is fine- to medium-grained, light grayish white with a slight greenish cast, and generally cross-bedded. It interfingers with the underlying Recapture Member and also with the overlying Brushy Basin Member.

The Brushy Basin mudstone is 25o to 35o feet thick in the area, and it contains numerous interfingerings and lenses of Morrison-type sandstone that vary in thickness and extent.

Overlying the Brushy Basin mudstone is the host rock for all economically important uranium deposits in the area. It has been informally designated by Freeman and Hilpert as the Jackpile sandstone bed of the Brushy Basin Member. Cross-bedding studies and other geologic data indicate that it was deposited from the southwest as channel filling in the Brushy Basin mudstone during a period of minor folding which tended to restrict the area of deposition to a belt more than 35 miles long, at least 15 miles wide, and up to at least 220 feet thick. Following its deposition, and prior to the beginning of Dakota deposition, an unknown thickness of Jackpile sandstone (and possibly overlying mudstone) was removed by erosion, and the Morrison was peneplained to a relatively flat surface. The nonconformance of structure contours on the bases of beds beneath it suggests that scouring may have occurred contemporaneously with the initial stages of Jackpile sandstone deposition, but in actuality this nonconformance is mainly due to interfingering of the sandstone and mudstone with resultant transition zones that obscure the exact position of the base of the Jackpile sandstone.

The Jackpile sandstone is predominantly grayish white with a slight greenish cast where it has not been exposed for a significant length of time; in the outctops, it is yellowish white because of the bleaching of contained kaolin and the formation of limonite stain.

Sandstone grains generally range in size from fine to medium, and consist mainly of subangular to subrounded particles of quartz, with minor amounts of disseminated feldspar. Sorting is usually fairly poor, particularly in the mineralized areas. Thin lenses and partings of mudstone are common throughout the entire sandstone.

According to Schlee and Moench (1961), the sandstone

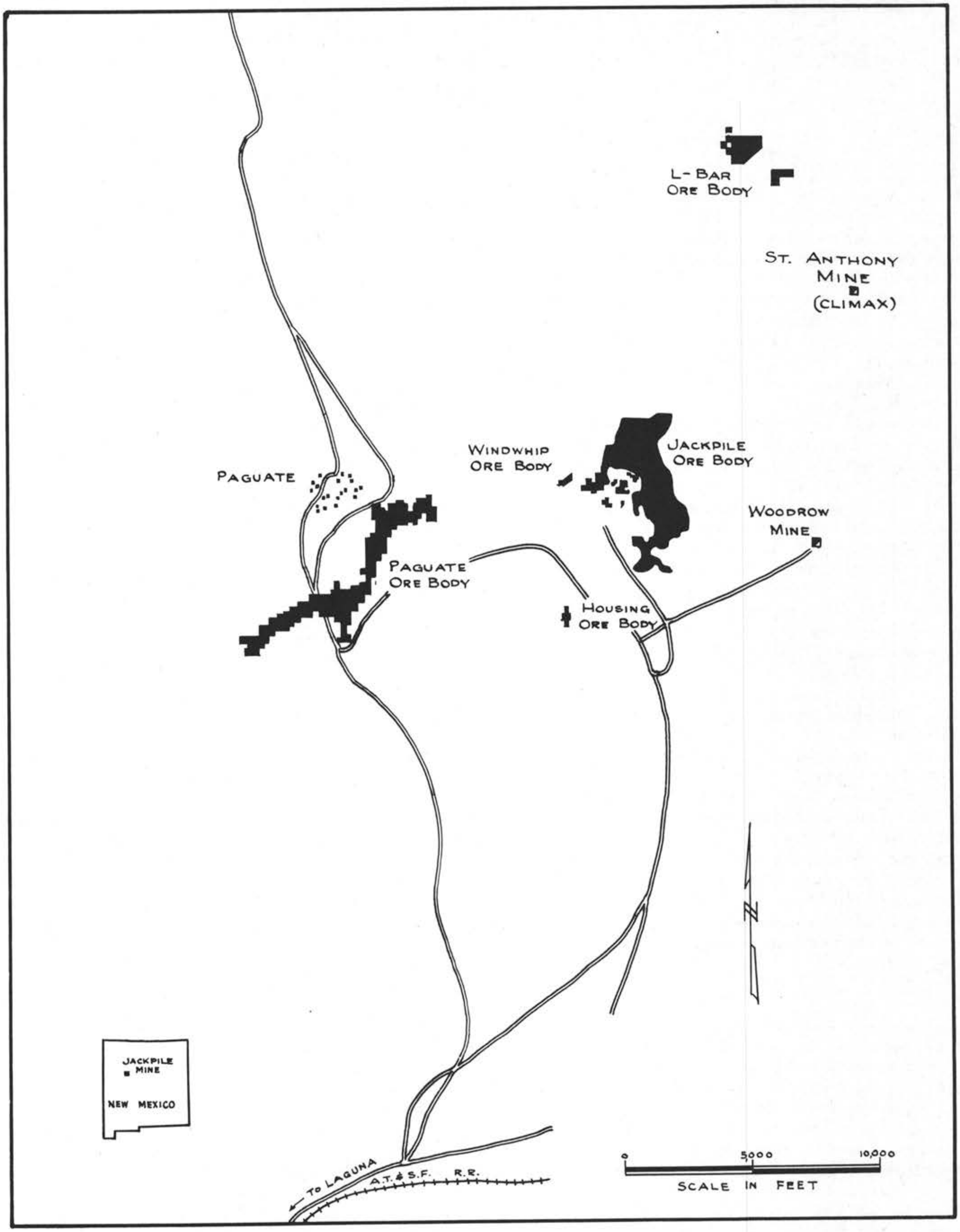


Figure 1

Index map showing the Jackpile mine area, Valencia County, New Mexico

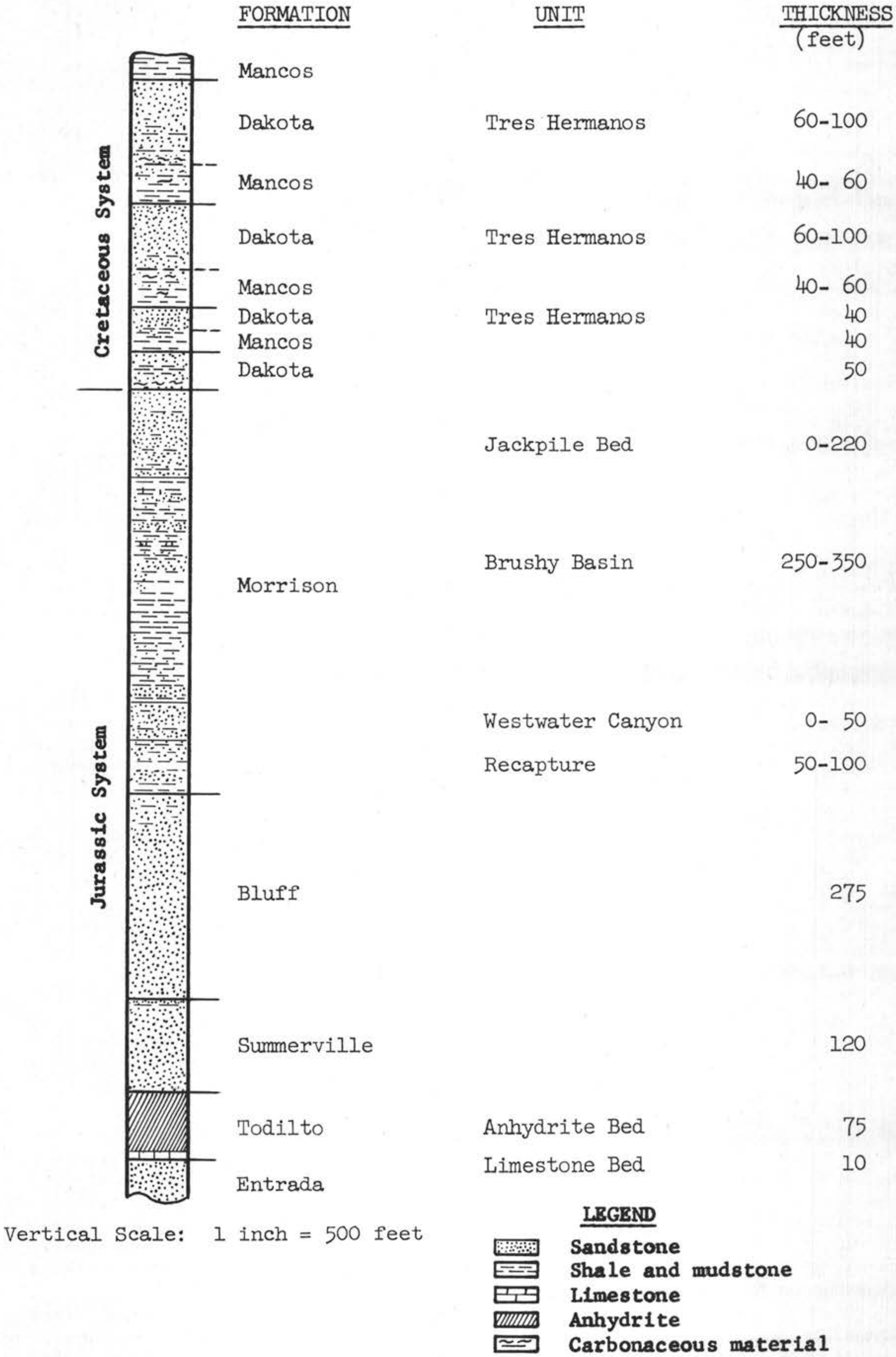


Figure 2

Generalized stratigraphic column of the Jackpile mine area cement is predominantly calcite near the base of the unit and becomes increasingly kaolinitic toward the top of the unit, probably as a result of more intense pre-Dakota weathering of contained feldspar.

Overlying the Jackpile sandstone bed is the Dakota formation. Its base is a hard, fine- to medium-grained, sugary-textured, rounded to subrounded sandstone that forms a capping over the Jackpile sandstone on many of the mesas in the area. The hard capping grades abruptly upward into about 4o feet of fairly soft, carbonaceous and shaly siltstone. The carbonaceous material is often coaly and often contains appreciable amounts of finely disseminated pyrite. The siltstone of the Dakota is usually capped by a few feet of fairly hard rim-forming sandstone.

Above the basal Dakota sandstone-siltstone unit are alternating horizons of black Mancos Shale and three sandstone units called the Tres Hermanos. The sandstone units vary in thickness from 4o to 10o feet, grade imperceptibly downward into Mancos Shale, and each is capped by a few feet of fairly hard, silica- and calcite-cemented sandstone that forms prominent rims in the area. The Tres Hermanos sandstones together with the basal "Dakota" bed are best referred to as the Dakota Group.

### IGNEOUS ROCKS

Several diabase dikes and sills are exposed in and near the Jackpile—Paguate area, and basalt flows cap the mesas to the west. One diabase dike two to three feet thick cuts through the southern part of the Jackpile deposit at an acute angle to the bedding. A similar sill occurs at the Dakota—Morrison contact in the northeastern part of the Paguate deposit, and a nearly vertical, north-south-trending diabase dike crops out from a point about one mile north of the village of Paguate, extends southward through the southwestern part of the Paguate ore body, and is lost to view in the talus and alluvium below the Dakota rim about three miles south of Paguate. Another diabase dike crops out for a short distance near the Woodrow mine. Several other less conspicuous dikes and sills are also found in the area.

Several centers of former volcanic activity are on the fringes of the Jackpile area, but it seems doubtful that there is any direct relationship between them and the uranium occurrences. However, it is possible that an indirect relationship might exist between the centers and the uranium deposits: deposition of the uranium may have been influenced by hydrogen sulfide gas that is normally emitted during periods of volcanism.

## STRUCTURE

The sedimentary rocks in the Jackpile area are generally flat-lying, with a regional two-degree dip to the north-northwest into the San Juan Basin as a result of post-Dakota tilting. As knowledge of the uranium deposits in the Grants district increased, it became apparent that post-Dakota structure in general had little or no influence on uranium deposition, whereas the reverse may be true of pre-Dakota structure. Thus, map techniques were developed to remove post-Dakota structure in the Jackpile area with a resultant picture of the areal structure as it existed at the end of Morrison time. These procedures (later verified by seismic work) showed that during deposition of Morrison sediments, existing beds were deformed by gentle warping along northeasterly trends. Deposition of the Jackpile sandstone was channeled by the warping to about its present position, and the greatest sandstone thickness was concentrated in a large, basinlike depression in the Paguate—Jackpile—St. Anthony area, bounded generally by the 100-foot contour line, as shown in Figure 3.

Of particular interest from the standpoint of structure is the Woodrow pipe and a similar collapse structure in the eastern part of the Jackpile mine. They are discussed separately elsewhere in this publication by E. T. Wylie and R. H. Moench.

Faulting in the area exists only to a minor degree. Several faults have been exposed in the Jackpile pit, but displacement along them reaches only a few feet. Moench and Puffett (1956) suggested that the regional fracture pattern was formed contemporaneously with the intrusion of the igneous rocks in the area.

## MINERALIZATION

To date the following uranium minerals have been identified from the Jackpile mine:

| | |
|---|---|
| Autunite | Phosphuranylite |
| Becquerelite | Schoepite |
| Carnotite | Sklowdowskite |
| Coffinite | Soddyite |
| Hydrogen-autunite | Tyuyamunite |
| Meta-autunite | Uraninite |
| Metatorbernite | Uranophane |
| Metatyuyamunite | |

Also occurring in the Jackpile and Paguate deposits are pyrite and quantities of selenium, molybdenum, and vanadium, which are for the most part noncommercial. The suite of minerals found in the Woodrow pipe is listed by E. T. Wylie in his article in this publication.

Although the predominantly black uranium mineralization in the Jackpile and Paguate mines is often referred to as coffinite, or "coffinite-type mineralization," metallurgical testing indicates that mill ore from those deposits normally contains about 2 percent coffinite, 8o percent unidentifiable oxidized uranium complexes, 15 percent uraninite, and 3 percent organo-uranium complexes.

Nearly all the uranium mineralization in the Jackpile mine occurs in the lower half of the Jackpile sandstone. The commercial ore ranges from 20 to 5o feet in thickness and is often separated into two horizons by a relatively barren layer of sandstone of variable thickness.

In the eastern part of the Paguate deposit, the commercial uranium generally occurs in the upper one third of the host rock, whereas in the western part, it occurs mostly in the lower two thirds. Figure 4 is a north-south cross section through the eastern part showing the cutoff of mineralization against the base of the Dakota sandstone. Although this is not typical of Paguate ore-body deposition, the mineralization is not uncommonly found emplaced in this manner in the eastern part.

Numerous controls have influenced to varying degrees the emplacement of uranium in the Jackpile area, the most apparent of which is the thickness of the Jackpile sandstone. Figure 3 shows that nearly all the Jackpile and Paguate ore occurs where the host sandstone is from 100 to 200 feet thick.

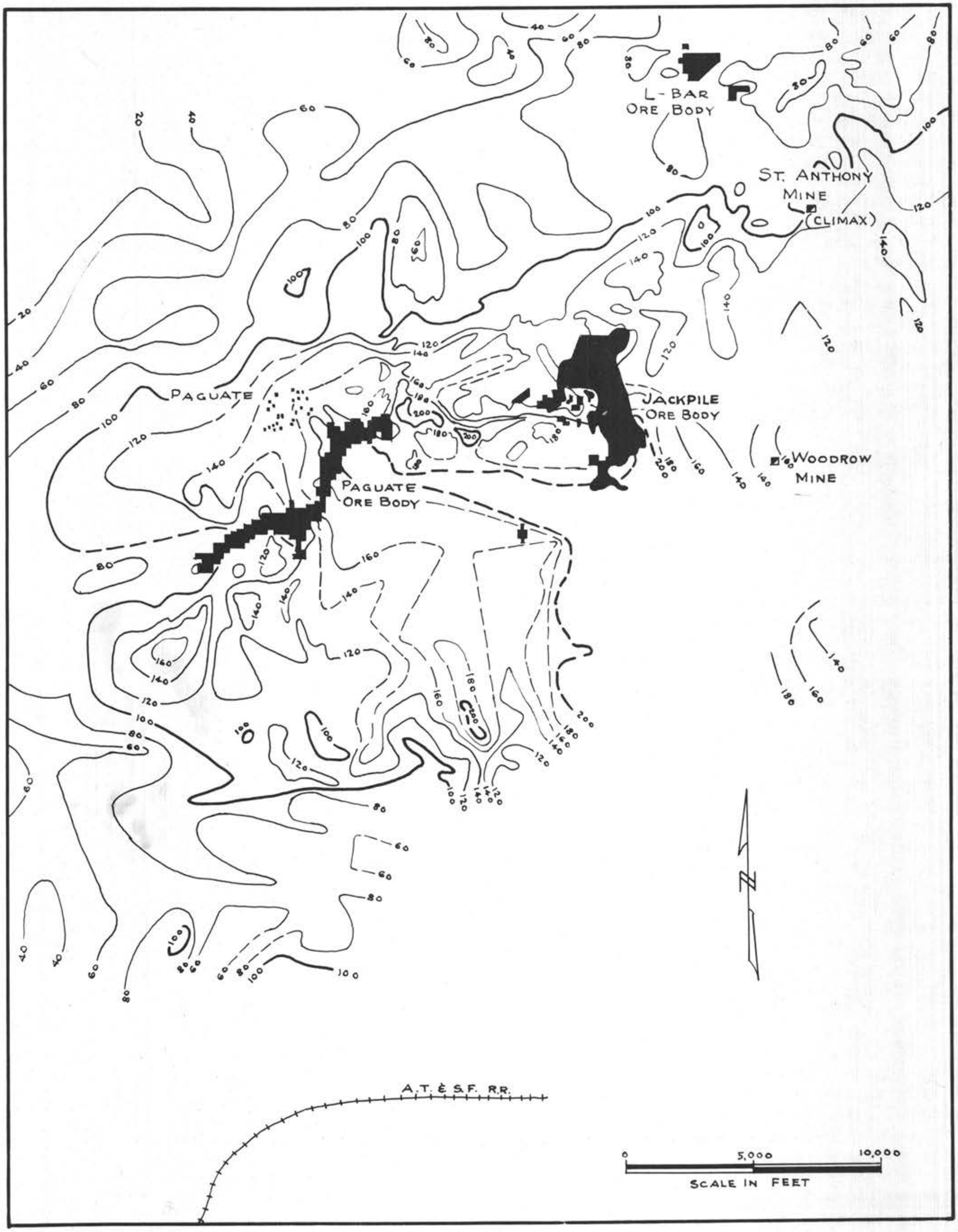


Figure 3

Jackpile mine area isopach map of Jackpile sandstone

The bulk of the ore is found in thick, but not the thickest, part. All mineralization is concentrated at or near one or more controlling features, such as carbonaceous material, mudstone layers and lenses, bedding planes, facies changes in the sandstone, and in some instances along weak intraformational faults. Cross-bedding sometimes exhibits well-defined local control of the mineralization, but many examples of transection of cross beds by mineralization also can be seen. Although mineralization is found at the contacts of sandstone and mudstone, it is more often found parallel to and a few feet above such contacts.

With the exception of the Woodrow pipe and the Jackpile mine collapse structure, obvious structural controls are not found in the Jackpile area. Subtle flextures in the Jackpile sandstone have been exposed by mining, but it is doubtful that they played a major role in the localization of the uranium It is believed that regional tectonics exerted considerably more influence in this regard, even though indirect, than did local structure.

Because of the intermittent and localized nature of cross-bedding and other minor sedimentary features, they can seldom be used as reliable guides for exploration. A drill hole that cuts one or more of them is normally cored or probed as a routine procedure for obtaining direct information; so, in the final analysis, the control feature that can best be used as an exploration guide is the thickness of the Jackpile sandstone. It can be projected with reasonable certainty outside a drilled area or from one area to another for distances of a few thousand feet.

Attempts to determine the age of the Jackpile area uranium by the lead-isotope ratios method have not been particularly successful to date. The relationship of the deposits to their environment suggests that they were emplaced in late Cretaceous to possible middle Tertiary time, after Dakota deposition and regional tilting, and prior to or during regional volcanism that is thought to have occurred in early to middle Tertiary time. To what extent the uranium has been transported and reconcentrated after original deposition is a matter of conjecture.

The genesis of the Jackpile area uranium deposits is an unsolved problem. Several theories have been advanced but none of them can be supported with evidence so conclusive

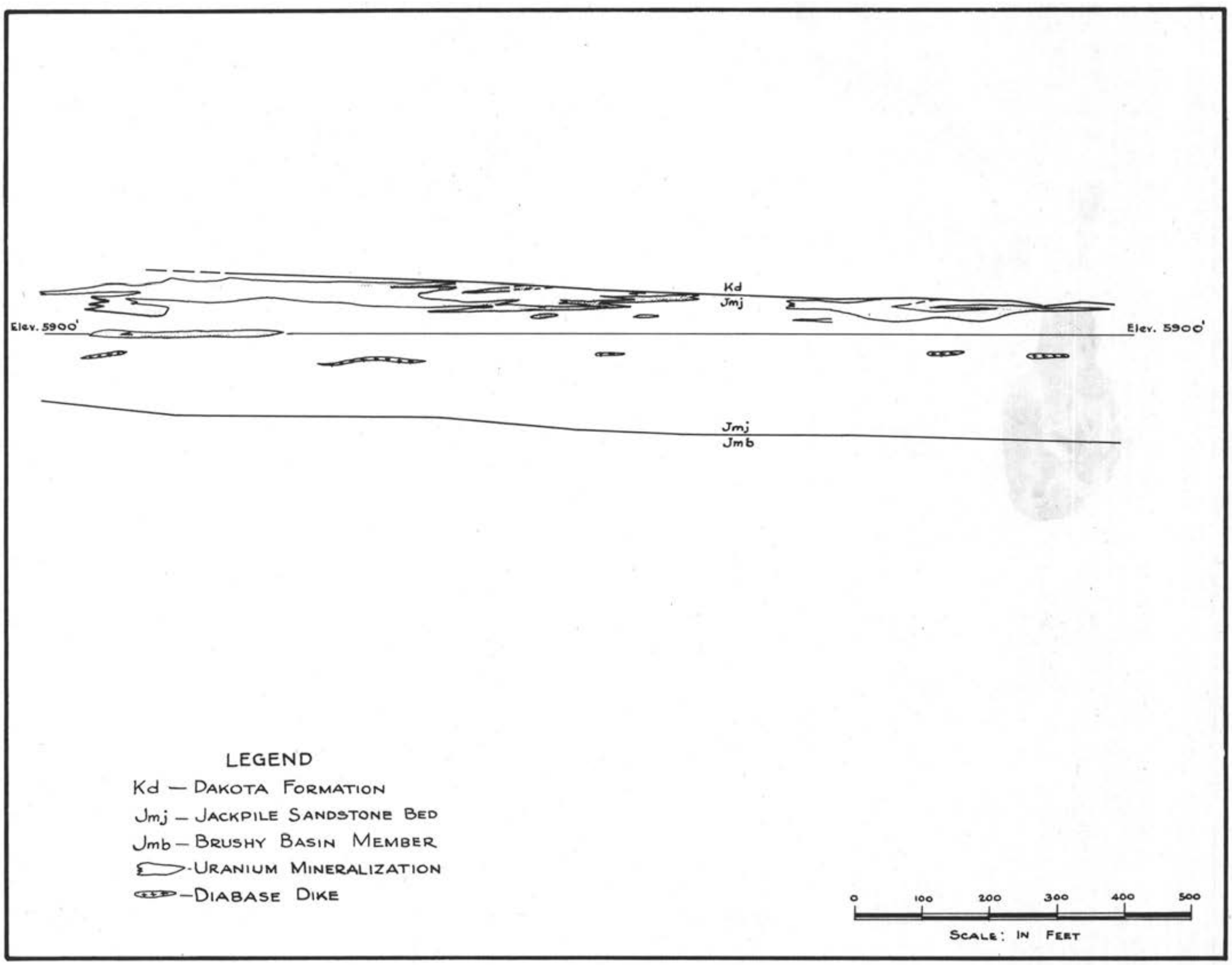


Figure 4

SECTION ACROSS A PART OF PAGUATE URANIUM DEPOSIT LOOKING WEST that it eliminates all other possibilities. Available evidence suggests that the uranium emplacement could have been the result of any combination of syngenetic deposition, hydrothermal deposition, and volcanic ash leaching by ground water.

If a syngenetic origin of the Jackpile deposits is to be considered, the question of a source immediately arises. The Morrison sediments are believed to be products of erosion of the ancient Mogollon highlands that once existed in west-central New Mexico. During the processes of erosion of the source area the constituent uranium was dissolved and transported by surface water to and through a favorable environment farther north, where it was reconcentrated in the present deposits. The supply of uranium could have been augmented by volcanic activity which is believed to have occurred in and around the source area during Morrison time.

Much of the Brushy Basin Mudstone is made up of volcanic ash that was deposited during Morrison time. The uranium in the Grants district may have been originally leached from the beds of ash and redeposited in its present host sandstones. If this was the source of the Jackpile area uranium, it would mean as much as a hundred million pounds of uranium was leached from overlying Brushy Basin Mudstone and redeposited in the Jackpile sandstone, in a manner similar to the formation of the deposits at Pumpkin Buttes, Wyoming (Love, 1952). During or after leaching of the uranium, the former host mudstones would have been nearly completely removed from the Jackpile area and redeposited farther north in the San Juan Basin.

With the exception of the Woodrow ore body, it does not seem likely that the uranium in the Jackpile area was emplaced *in situ* by hydrothermal processes. However, there are definite indications that the tabular deposits may have been formed by the introduction of uranium-bearing hydrothermal fluids (or gases) into surface and near-surface waters in the area by means of deep-seated conduits, such as Woodrow-type pipes, or through deep-seated fractures which later became passageways for dikes and sills. After introduction of the uranium into the migrating ground water, it could have been redeposited in chemically and lithologically favorable environments. Data that support this theory of genesis are as follows :

. The Woodrow pipe contained a suite of minerals that is indicative of a hydrothermal origin. The type of mineralization and the nature of its occurrence suggest that the Woodrow pipe could either have served as a conduit for ascending uranium-bearing fluids or may have acted as a trap for them so that the uranium in the solutions which entered the pipe was never released into the surrounding beds.

2. Downdip migration of uranium-bearing fluids from centers of ground-water contamination is suggested by the orientation of the axes of the Jackpile and L-Bar—St. Anthony deposits with the axis of regional post-Dakota tilting as shown in Figure 5. Near the Paguate deposit, generally weak and erratic mineralization to the south (not shown on the included maps) conforms to the same trend, indicating that mineralizing fluids could have migrated in the same manner from a center of contamination and encountered a paleostream channel that provided a suitable environment for deposition of the dissolved uranium. Maps of known mineralization in the area support these data and also show a general alignment of the longitudinal axes of barren areas between the deposits with the axis of regional dip.

3. Numerous heretofore undetected Woodrow-type pipes could be present in the Jackpile area, overlain by sediments or alluvium.

4. The position of the uranium mineralization in relation to the base of the overlying Dakota, as illustrated in Figure 4, indicates that uranium deposition occurred after regional tilting. The slight general decrease in elevation from south to north suggests the influence of ground water that was migrating downdip after regional tilting occurred.

The acceptability of this hypothesis is dependent to a considerable degree upon the time at which the proposed Woodrow-type pipes formed. Their age would necessarily be younger than the regional tilting that is postulated to have occurred during early to middle Tertiary time and older than the late Tertiary emplacement of the sill that cuts the Jackpile mineralization. Because the top of the Woodrow pipe has been eroded away, the time of its formation is largely a matter of conjecture. If it and the Jackpile mine collapse structure are contemporaneous, it was formed while the Jackpile sandstone was being deposited, and the foregoing hypothesis of genesis could be adequately supported only by dating the uranium deposition to Morrison time or by theorizing that during Tertiary time a rejuvenation of igneous activity resulted in the ascension of uranium-rich fluids into the pipe. However, it is also possible that the Woodrow pipe and other cryptostructures similar to it were formed during Tertiary rather than Morrison time.

The theory that uranium-rich solutions may have been introduced into migrating water in the Jackpile sandstone through deep-seated fractures which were later filled by the diabase sills and dikes in the area can be supported fairly well from the standpoint of time sequences, but the question arises as to the preferential deposition of uranium in a particular unit that is lithologically similar to other units in the Morrison formation. Another discrediting factor is the seeming lack of any close relationship between the mineralization and the former fissures. There is no apparent concentration of uranium in proximity to them, and in many instances the dike areas are completely barren. These circumstances could be explained only by the possbile redistribution by ground water of the uranium after its introduction into the Jackpile sandstone.

Results of a study by S. R. Austin (196o) concerning the alteration of the Morrison sandstones in the Grants district tended to support the possibility of a hydrothermal origin of the Jackpile uranium deposits. The study indicated that the Morrison sandstones of the Grants district first underwent alteration in a reducing environment, probably at the time of uranium deposition; then at a later time certain areas outlying from the ore zones were subjected to oxidizing conditions that produced the brown, yellow, and red coloring of the Morrison sandstones in many parts of the district. According to Austin, the alteration produced by the reducing conditions mineralogically resembles the effects of hydrothermal alteration, but it cannot be unequivocably stated that it was caused by hydrothermal alteration.

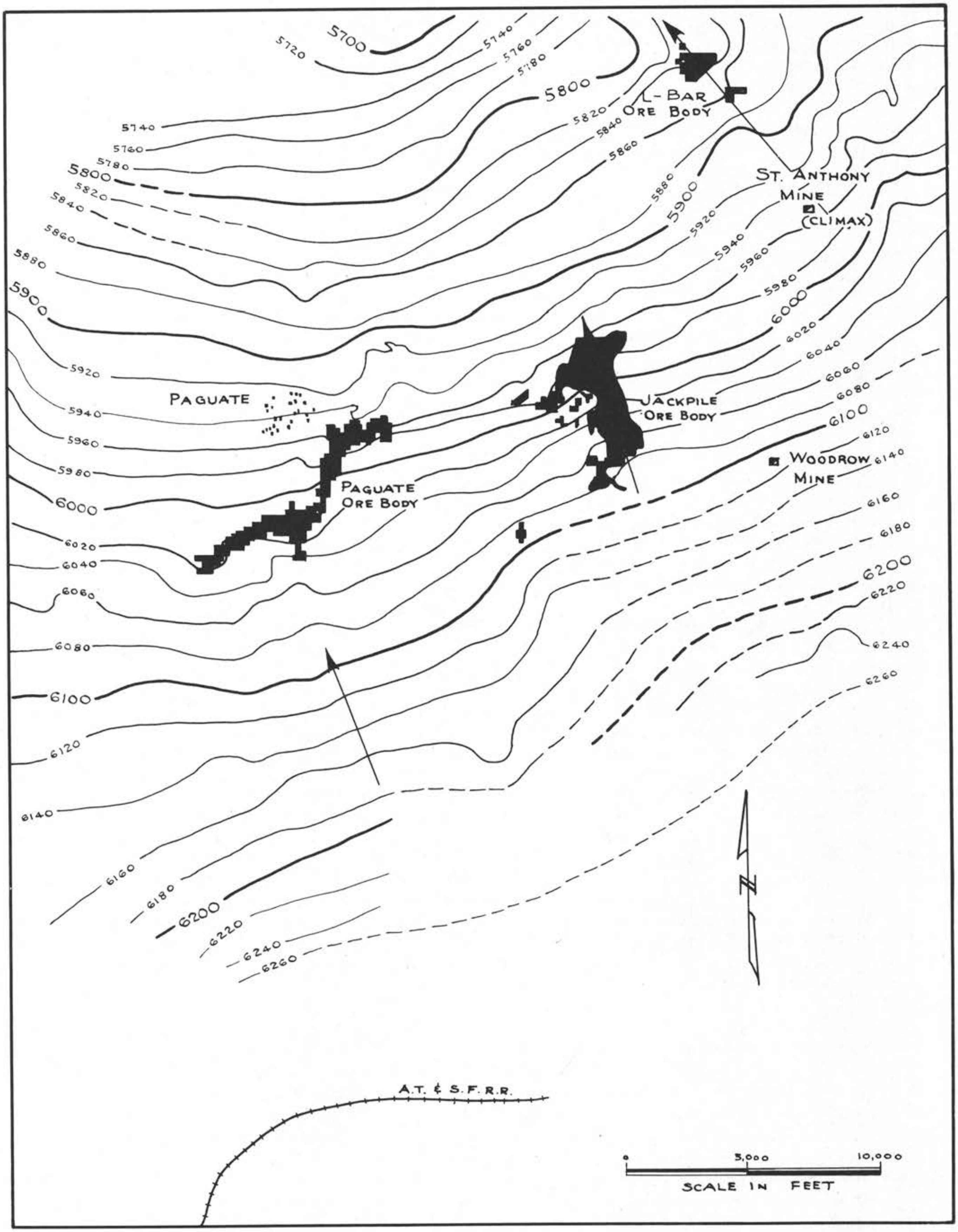


Figure 5

JACKPILE MINE AREA STRUCTURE CONTOUR MAP ON THE BASE OF DAKOTA FORMATION

Figure 6

View south along the Jackpile open-pit mine. Sandstones of the Dakota Group form the near ledges on the left, the mesa remnant to the west of the pit, and the lower mesa across the valley to the right. The high mesa on the right is capped by basalt flows of the Mount Taylor volcanic field

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# Geology of the Woodrow Breccia Pipe

ERNEST T. WYLIE

## INTRODUCTION

The Woodrow mine is about one mile east of the Jackpile mine on the Laguna Indian Reservation in Valencia County, New Mexico. The deposit was discovered by an aerial scintillation survey in 1951 and was mined in two stages during 1954 and 1956. During the first phase of the operation in which the area from the r oo-foot level to the surface (fig.1) was mined, the average grade of ore was 1.53 percent U308, o.o5 percent $V_2 0_5$, and 1.4 percent $CaCO_3$.

The second phase of the operation mined the area from the zoo- to the 100-foot level, and the average grade of the ore declined to 0.32 percent $U_3 0_8$, o.03 percent $V_2 0_5$, and 1.2 percent $CaCO_3$. No determined exploration effort below the 200-foot level was made as the grade would have had to be quite high to justify mining the very small tonnage involved.

## GEOLOGIC SETTING

The Woodrow pipe lies in the Acoma sag of the southern fringe of the San Juan Basin. The pipe here is entirely within the Jurassic Morrison Formation, though it probably extends much deeper into the underlying Bluff Sandstone, Summerville Formation, and Todilto Formation.

The Morrison Formation is locally divided into four units. Ranging from upper to lower they are Jackpile sandstone, Brushy Basin Member of mudstone and sandstone, Westwater Canyon Member of sandstone, and Recapture Member of shale.

## DESCRIPTION OF DEPOSIT

The structure is a breccia pipe about 24 to 34 feet in diameter and nearly circular in plan. The pipe is steeply dipping, the strike and dip above 5951 feet elevation averaging S. 5o° E. in strike and 67 degrees in dip. Below 5951 feet elevation, the pipe spirals to the northeast and develops an average strike of N. 45° E. and a dip of 83 degrees for the remainder of its known extent.

The pipe crops out in the Jackpile sandstone at the surface with both the exterior and interior parts of the pipe consisting of Jackpile sandstone. It penetrates Brushy Basin mudstone and sandstone beds below the Jackpile sandstone and the ring-fault structure is as strong in the mudstone on the 200-foot level as at any elevation in the mine.

A crosscut intersects the pipe 200 feet below the surface and a core-drill hole is probably still within the pipe 118 feet below the 200-foot level. The last stratigraphic offset that can be determined with certainty is 72 feet below the 200-foot level *(see* bed "A" in fig. 1) and shows an approximate 31-foot drop compared to the same beds outside the pipe.

The bottom of the Jackpile sandstone in the pipe compared to the outside indicates a drop of 3o to 45 feet, depending upon which block is measured. The sandstone labeled "B" on the section indicates a drop of approximately 45 feet.

I have not detected the drag or sagging indicated by Hilpert and Moench (196o, p. 457) in the surrounding beds. Indeed, the beds are remarkably unwarped, and the sandstone beds particularly show a sharp, clean break where the ring fault penetrates them. The mudstone generally does show some drag effects for a few inches, but it is quite minor. There is little in the way of branching faults, except for a few in the 5947- to 5967-foot zone.

The mudstone parts of the interior of the pipe are usually well brecciated with no fragments more than one foot in diameter, and the average is much below this figure. The sandstone areas of the interior of the pipe tend toward larger fragments, except near the ring fault where they are usually more brecciated The center of the large Jackpile sandstone block in the upper part of the mine is relatively unbrecciated in its lower portions, indicating that this part probably dropped as a unit. There is extreme brecciation around the 5950-foot elevation in this block of sandstone that is probably the result of the change of strike and dip at this horizon.

The uranium mineralization in the upper part of the pipe is concentrated in the fault zone, permeating the interior of the pipe where a particularly favorable horizon occurs. Such a horizon is found between the 5947- and 5967-foot elevation in the pipe. There are three factors which probably contributed to the concentration of high-grade ore in this zone:

. The contact between the Jackpile sandstone and the Brushy Basin Mudstone on the exterior of the pipe is in this horizon. This is probably the weakest contributing factor.

2. This is the zone in which the pipe changes strike and dip.

3. The sandstone in the interior of the pipe at this horizon is thoroughly brecciated.

These factors combined to form a very favorable host horizon, and it is this zone that made the mine a paying proposition. Samples as high as 20 percent $U_3 0_8$ were obtained from this area. In this horizon the mineralization locally extended ten feet outside the ring fault, following minor fractures and the favorable sandstone horizons.

The uranium mineralization between 5817- and 5912-foot elevation is confined to the interior of the pipe and very little is found in the ring-fault zone, in direct contrast to the area above. Gray-green brecciated mudstone fills the pipe inside the fault ring in this zone. The FeS2 and black uranium mineralization occupies the interstitial areas of the breccia in the lower part of this area from the 5817- to 5853-foot elevation. At about 5853 feet elevation, a change occurs and the mudstone takes on a darker color due to the permeation of the black uranium mineralization in the breccia fragments. The FeS2 is still generally confined to the interstitial area. It was from this 5853- to 5894-foot elevation that the best grade of ore was obtained between the 200- and 100-foot levels.

In Figure 1, the figures shown in columnar fashion in the raise represent the $U_3O8$ averages for the samples in a two-compartment raise area. These averages clearly demonstrate

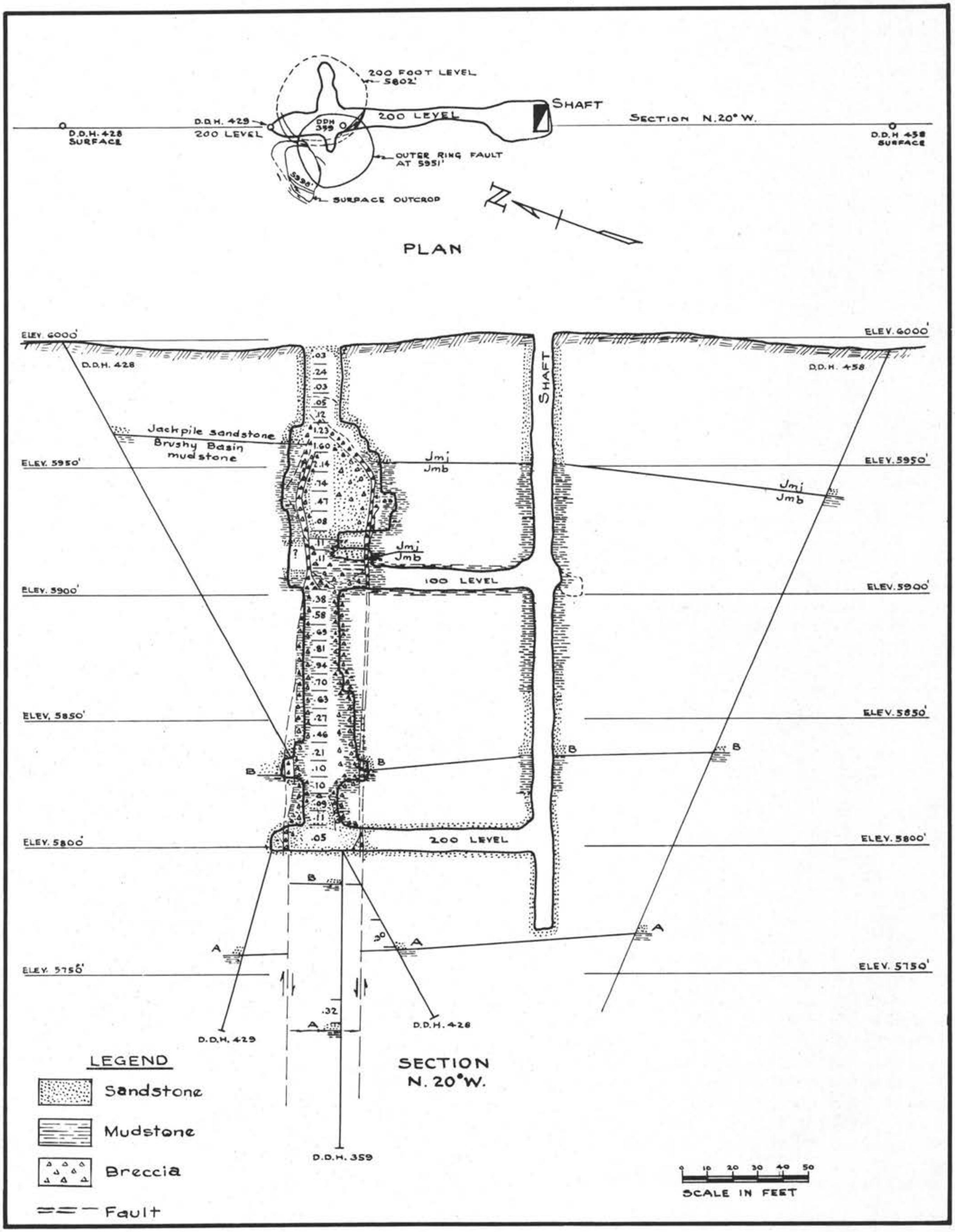


Figure 1

PLAN AND SECTION OF WOODROW MINE, JACKPILE MINE AREA where the best $U_3O_8$ ore was to be found. No averages are available for the 100-foot level crosscut area, but the values here were very low in $U_3O_8$ but quite high in $FeS_2$.

The figures below the 200-foot level on D.D.H. 359 and D.D.H. 428 in Figure I represent the $U_3O_8$ values obtained from cores of this sandstone horizon. The sandstone in this "A" horizon was very coarse-grained with some fragments up to 8 mm. Much carbonaceous trash was present in this core and seemed to contain the major part of the uranium mineralization. I think that this horizon presented a favorable host to the mineralizing solutions and was faulted before mineralization.

The sandstone bed "A" furnishes from 15 to 20 gallons a minute of water to the shaft and is pumped for Jackpile mine use.

A sample obtained from the 594o-foot elevation in the pipe was sent to Lester G. Zeihen, Anaconda mineralogist, for mineral identification. A photograph of the sawed and polished half of this specimen is reproduced in Figures 2 and 3. Mr. Zeihen (1956) reported this specimen as follows:

> This specimen is largely composed of pyrite and minor marcasite. Due to the fine-grained texture and intimate mixture with other minerals, it is nearly impossible to distinguish much of the pyrite and marcasite. The massive pitchy black mineral in this specimen is coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$, associated with minor uraninite and possibly some carbonaceous material. Identification was made by X-ray diffraction patterns and autoradiogram. It will be noted on the figures that certain areas contain very finely divided pyrite apparently suspended in a matrix largely composed of coffinite (carbonaceous material? and minor pitchblende). The intense radiation in the narrow zones adjacent to much of the irregular

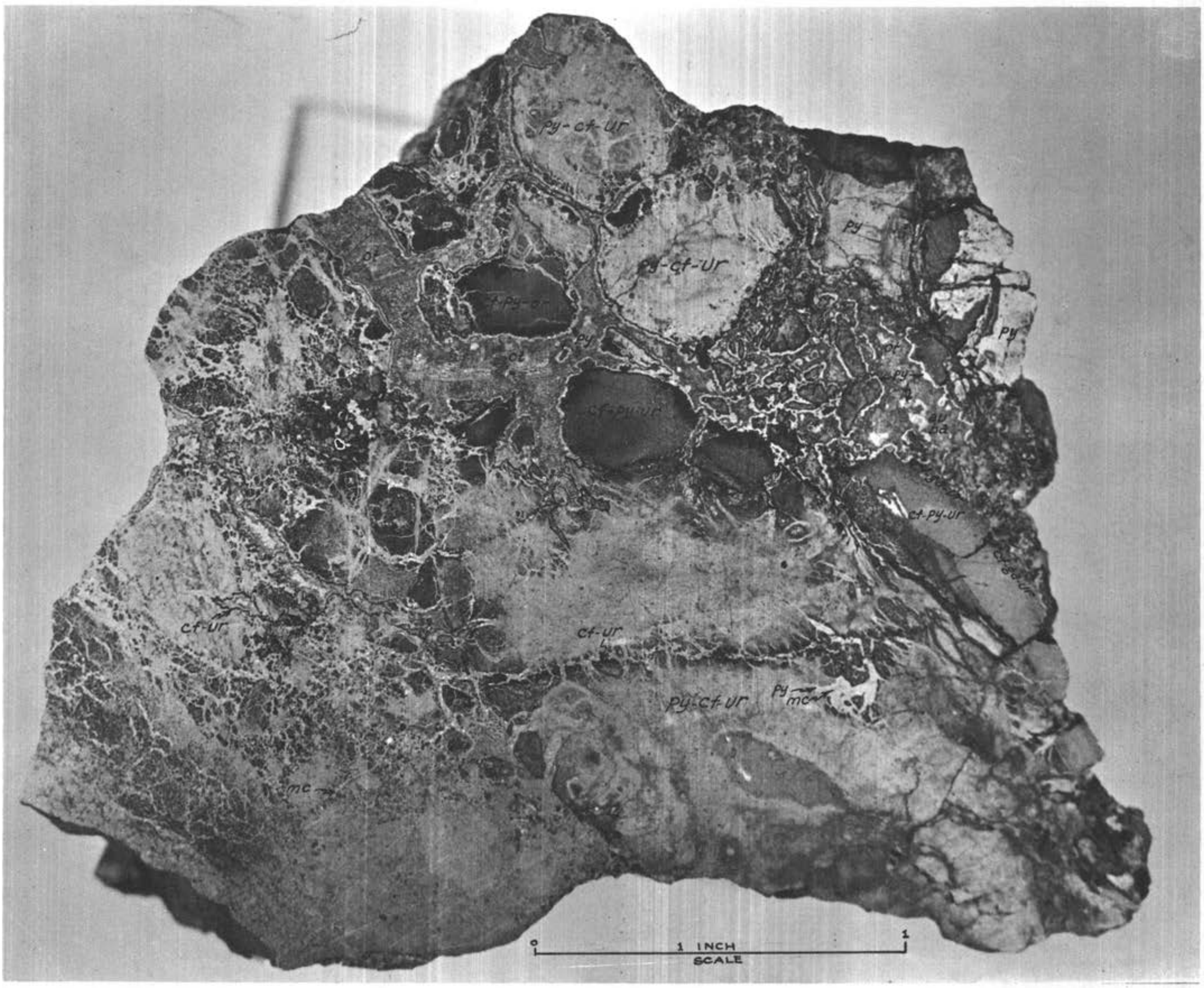


Figure 2

POLISHED SLAB OF SULFIDE ORE FROM ELEVATION 5940 IN THE WOODROW PIPE

Pyrite, py (white); marcasite, mc (white); coffinite, cf (black); uraninite, ur; barite, ba.; meta-autunite, au; galena, ga; and organic texture (?) ot. Oblique illumination.

pyrite-banding in the breccia of this specimen is not yet explained. Meta-autunite, $Ca(OU_2)2(PO4)2 \cdot 2\ 1/2\text{-}6\ 1/2\ H_20$, and barite have been identified from this zone but it is doubted that they alone could be responsible for the strong exposure observed. Meta-autunite is the only secondary uranium mineral identified in this specimen. Platy crystal groups are found as crack fillings and irregular cavity fillings wherever pore space is available. Certain textures in the pyrite of this specimen resemble cell structure such as observed in bone or plant replacement. [fig. 2] A microscopic study of the polished surface with vertical illumination (may also be observed with oblique illumination under the binocular microscope at 10x to 30X; *see* location in fig. 2) showed a series of minute square crystal outlines with bright white metallic reflections included in a black waxy matrix bordering certain of the finely divided pyrite-coffinite zones. An X-ray diffraction pattern identified these as galena in a coffinitepitchblende-asphaltite (?) mixture.

The marcasite in this specimen appears to be present principally as fine veinlets or central areas surrounded by pyrite.

Summary of the minerals from the Woodrow mine, either positive or tentative identifications from all sources, is as follows:

Autunite — Ca(UO2)2(PO4)2 *10-12H2O
Novacekite — Mg(UO2)2(AsO4)2*8-10$H_2O$
Torbernite — Cu(UO2)2(PO4)2*8- 1 2$H_2O$
Meta-autunite — Ca(UO2)2(PO4)2*2 1/2-6 1/2$H_2O$
Coffinite — U(SiO4)1-x.(OH)4x.
Uraninite — UO2
Johannite — $Cu(UO_2)_2(SO_4)_2(OH)_2.6H_2O$
Becquerelite — $2UO_3{*}3H_2O$
Uranopilite — (UO2)6(SO 4) (OH)10*12H2O
Zippeite — (UO2)2(SO4) $(OH)_2{*}4H_2O$
Metatorbernite — Cu(UO2)2(PO4)2*8H2O
Pyrite — $FeS_2$
Marcasite — FeS2
Barite — $BaSO_4$
Galena — PbS
Chalcopyrite — CuFeS2
Jarosite — $KFe_3(OH)_6(SO_4)_2$
Sabugalite — H(Al) (UO2)4(PO4)4*16 $H_2O$

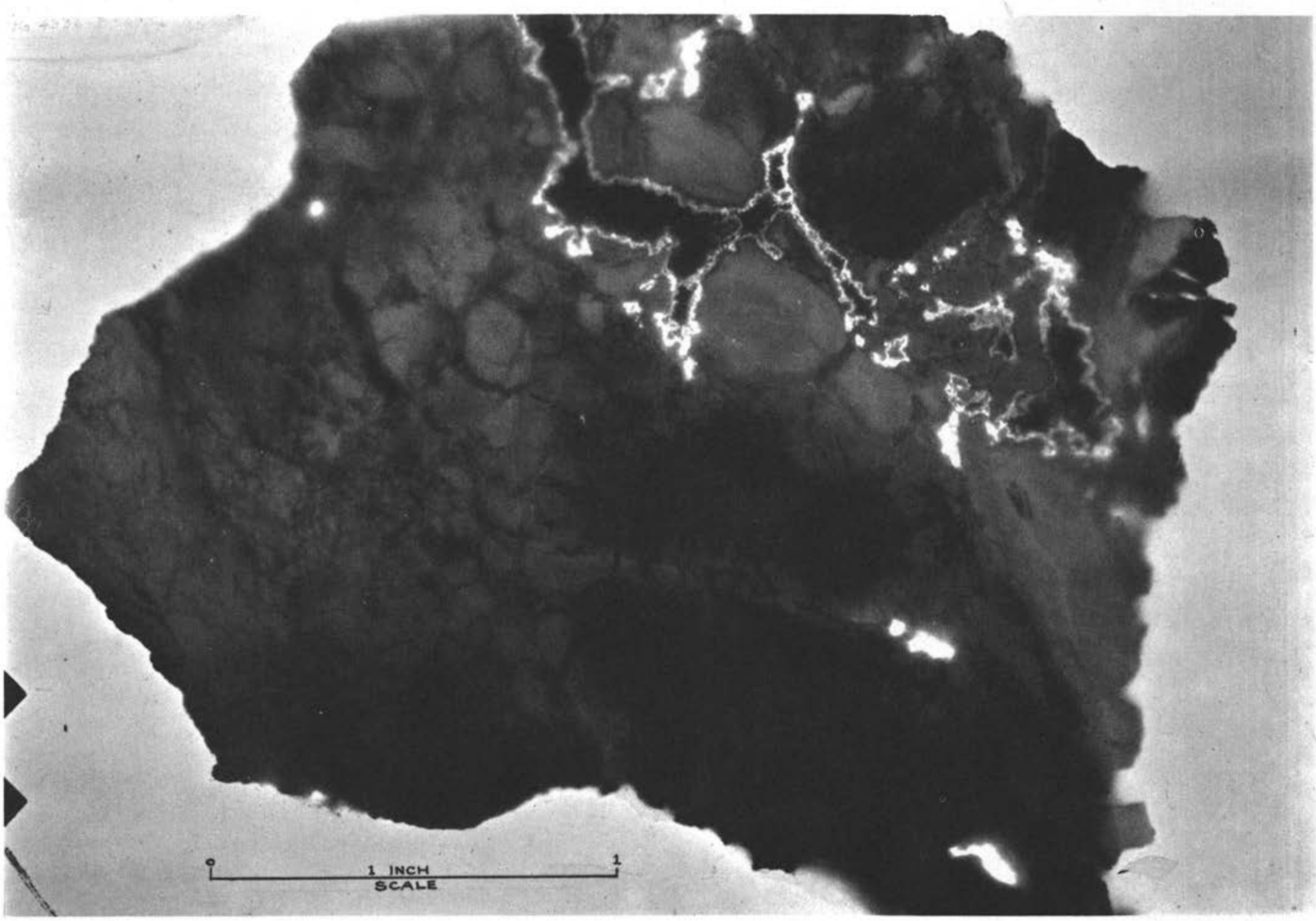


Figure 3

AUTORADIOGRAM OF THE SPECIMEN OF FIGURE 2

The material responsible for the intense radiation has not been positively identified. Irregular dark-gray to black areas are principally iron sulfides.

Carbonaceous materials are present within the pipe but represent no greater concentrations than are found locally in the Jackpile sandstone and Brushy Basin Member.

## GENESIS

The genetic problems of the Woodrow breccia pipe have caused several divergent views to be expressed. Perry (1961, p. 373) indicated a probable connection with deep-seated igneous activity. Hilpert and Moench (p. 456), on the other hand, believed that it is a sedimentary slump feature and is of the same origin as many other slumps observed in the area.

The Jackpile breccia pipe has been described by Hilpert and Moench (p. 442). It is relatively unmineralized except for a high-grade concentration of U3O8 adjacent to the western side of the pipe. The top of this pipe reached the surface during Jackpile time *(see* Hilpert and Moench, p. 442) and was buried by additional Jackpile sandstone. This makes it appear most likely that the date of formation was late Jackpile time. In all probability, the Woodrow pipe is this same age, but unimpeachable evidence is lacking. It is believed that the Woodrow and Jackpile pipes are not the same type of slump feature as that mentioned by Hilpert and Moench (p. 44[1]) in their discussion of "sandstone" or "breccia" pipes.

The Jackpile sandstone contains sanidine and relatively unworked quartz fragments *(Austin*, this memoir), indicating a nearby source for the Jackpile sandstone. V. C. Kelley has found bipyramidal, high-temperature quartz crystals in sandstone near Gallup (oral communication). These features, together with bentonitic claystones, indicate nearby igneous activity during late Jurassic time. It is possible that gases from these magma sources supplied the pressure necessary to drill pipes such as the Woodrow, Jackpile, and others. The same igneous surge that gave rise to the Morrison volcanics and the pipes may have mineralized the Woodrow pipe and possibly supplied uranium to the surface and subsurface waters that mineralized the Jackpile sandstone.

It is likely that more of these mineralized breccia pipes will be demonstrated in the area, and there is some suggestion of two buried pipes in the Paguate area.

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# *Sulfur Isotopes and Biogenic Origin of Uraniferous Deposits of the Grants and Laguna Districts**

M. L. JENSEN

## INTRODUCTION

Although field geology is the foundation for mineral genesis studies, many other "tools" have been of prime assistance in aiding the student of ore genesis. None of these "tools" will ever be a panacea to the study, but some of them have provided significant information, especially when correlated with field data. The mass spectrometer is one tool that has provided further light on the origin of certain mineral deposits by determinations of variations in stable sulfur isotopic abundances which bear on the genesis of sandstone-type uranium deposits.

This particular study was initiated as the result of several sulfur isotopic determinations on pyrite samples associated with uranium mineralization that I had collected from the Big Indian Wash district, Utah. The unusually high enrichment of $S^{32}$ in these specimens led to an extensive sulfur isotope study of sulfur-bearing minerals associated with uranium deposits (Jensen, 1958; Field, 196o; Cheney, 1963).

## BASIC CONCEPTS

There are more than 270 stable isotopes in nature that represent specific species of the elements. A specfic nuclide of an element is shown by the unique chemical symbol with the addition of a subscript at the lower left and a superscript at the upper right of the symbol. The subscript is the atomic number (Z) of the specific isotope, determined by its number of protons, while the superscript represents the mass number (A), or the total number of nucleons; that is, protons plus neutrons. The stable isotopes of sulfur, for example, are represented as follows: $16S^{32}$, $16S^{33}$, ${}_{16}S^{34}$, and ${}_{16}S^{36}$. The subscript is usually omitted as the unique chemical symbol identifies the atomic number.

The chemical properties of an element depend essentially upon the number and configuration of the orbital electrons, especially the electronic configuration of the outer shell. As the nuclides of a given element all have the same number of electrons, the nuclides of a given element behave alike chemically, and as their cosmic abundances were determined during or soon after the origin of the solar system, one might expect the stable nuclides to be found together in a relatively constant isotopic abundance regardless of the geologic occurrence or age of the specimen.

On the other hand, however, it is known that the isotopes of any element differ slightly in their rate of chemical behavior because of the slight differences in the thermodynamic properties of these isotopes, properties that are determined for the most part by their mass and atomic structure. In fact, because of these slight thermodynamic differences, the specific rates of reaction of the different species of one element do differ slightly, even though all do behave chemically alike.

In the case of sulfur, numerous mass spectrometric analyses indicate that meteoritic troilite contains almost precisely 22.22 times as much $S^{32}$ as it does $S^{34}$; that is, all troilites exhibit a ratio of $S^{32}/S^{34}$ equal to $22.220 \pm 0.004$ (Jensen, 1963; Thode, Monster, and Dunford, 1962). In contrast, mass spectrometric analyses of sulfur-bearing minerals collected from heterogeneous sources from the earth exhibit variations from this ratio ranging from a low value of 20.8 to a high of 23.6, a variation greater than 12 percent, while the precision of the mass spectrometric measurements is at least $\pm$ 0.02 percent. The meteoritic value is assumed to be very near to the $S^{32}/S^{34}$ ratio of primordial earth sulfur; variations from this ratio indicate geologic processes that have resulted in isotopic fractionation of sulfur resulting in either a loss or gain of, for example, the heavy ($S^{34}$) species.

Instead of indicating the isotopic composition of sulfur-bearing substances" as a ratio of $S^{32}/S^{34}$, the variation of a given ratio from the composition of meteoritic troilite is expressed as a permil variation according to the relationship

$$\delta S^{34}\,‰ = \frac{S^{32}/S^{34}\,(\text{standard}) - S^{32}/S^{34}\,(\text{sample})}{S^{32}/S^{34}\,(\text{sample})} \times 1000.$$

$\delta S^{34}$, therefore, is the permil variation of a given sample from the troilite ratio of 22.220; for meteorites, $\delta S^{34} = 0‰$. Positive values indicate enrichment in the heavier ($S^{34}$) isotope.

All mechanisms and processes that can cause fractionation of isotopes in nature are of applicable interest, because isotopic ratio variations may not only suggest the specific processes that have occurred but they provide us with a fuller understanding of the relative importance of the different natural physical and chemical processes.

## SULFUR OF BIOGENIC ORIGIN

The possibility of determining, with the aid of sulfur isotopes, whether sulfur has been derived from an inorganic source or from a biogenic source, has provided some hope that more diagnostic evidence might be provided to better determine which of two vastly different processes has resulted in the formation of certain mineral deposits.

It has become evident, not only from the thousands of sulfur isotopic measurements made, but also from theoretical

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considerations, that sulfur of biogenic origin exhibits a much greater spread in δ $s^{34}$ values than does sulfur of inorganic origin (Kaplan, Rafter, and Hulston, 196o; Jensen, 1959; Nakai and Jensen, 196o). The greater fractionation of sulfur isotopes by biogenic processes results from oxidation-reduction mechanims, whereby, for example, sufate ($SO_4$=) is reduced to sulfide (S=) by sulfate-reducing anaerobes. This is a resulting change in valence of the sulfur from 6 to — 2, respectively, which is a significant energy change. The sole process by which this reduction occurs in nature at temperatures of a few hundred degrees C and less is by sulfate reducing bacteria (as a geologist, I almost always avoid the phrase, "the sole process," but in the previous sentence, its use is warranted).

Theoretically, according to the specific isotopic exchange reaction, namely $H_2S^{34}$ + $S32O_4$= ↔$H_2S32$+$S34O_4$ = at and under equilibrium conditions, whether it be an organic or inorganic reaction, there should be a δ $s^{84}$ change of about 73 permil between the $H_2S$ and the $SO_4$= (Tudge and Thode, 1956). Of course, the reaction rarely, if ever, even approaches equilibrium, but δ $S^{34}$ variations in nature as great as 46 permil have been measured (Kaplan, Rafter, and Hulston) between sulfides and associated sulfates from which it is believed the sulfide sulfur was derived by anaerobic reduction. Generally, however, the variation is less than 20 permil.

To better understand the δ $s^{34}$ characteristics of biogenic sulfur, Nakai and Jensen have determined the S S34 composition and rate of hydrogen sulfide production of this gas from raw culture experiments in the laboratory with anaerobic bacteria, presumably of the *Desulfovibrio* genus.([1]) By collecting the gas produced by the anaerobes from the raw culture cells, we have endeavored to determine what factors have a bearing on the yield and extent of isotopic fractionation of hydrogen sulfide. Through these studies, it is apparent that the metabolic behavior of the anaerobes can be varied considerably by different factors. For example, the rate of production of hydrogen sulfide has been increased by more than 5o times by adding a few ml of the nutrient, sodium lactate, to a raw culture cell containing 450 ml of sea water having a concentration of 725 mg of S (as $SO_4$=) per liter, and 8o g of marine mud from Long Island Sound, Connecticut, containing the anaerobes. As the sulfate was reduced to hydrogen sulfide by the anaerobes, the evolved gas was passed through a solution of cadmium acetate where the sulfur was precipitated as a relatively insoluble sulfide, and the concentration and isotopic composition of the sulfur was subsequently determined.

Figure 1 is a graphical representation of the results of one of these experiments. The original concentration of 725 mg/1 of S in the form of sulfate was decreased to 62.5 mg/1 in less than five days by the anaerobes. As the result of the evolution of the biogenically produced hydrogen sulfide, the sulfate content decreased and the 2/S34 composition of the remaining sulfate changed from 21.77 to 21.46, because the escaping hydrogen sulfide was enriched in the lighter isotope. 'The actual amount of hydrogen sulfide that was collected, however, was surprisingly low, but still enriched in S32. The dashed curve on Figure 1, labeled S=, shows the actual amount of sulfur that must have been produced by the anaerobes, as this quantity must be equal to the amount by which the sulfate was reduced. Yet, as indicated by the curve labeled $H_2S$, only a very small amount of hydrogen sulfide escaped from the cell to be collected.

What did happen is that most of the hydrogen sulfide reacted so rapidly with ferric iron in the mud to form sulfide that it did not have an opportunity to escape! Proof of this inference is that the original content of sulfur as sulfide in the mud was 0.51 mg/g of wet mud which, following the experiment, had increased to 1.62 mg/g of wet mud. The change, moreover, in isotopic composition of sulfide in the mud from 22.44 to 22.15 is added proof that a significant quantity of sulfur with an isotopic ratio composition less than 22.15 was added to the mud where it formed sulfides.

Laboratory experiments are often cited erroneously as proof of specific geologic processes. Nevertheless, this experiment does suggest the rapidity by which sulfides of iron may form in nature by a reaction between hydrogen sulfide and ferric iron, presumably by the reaction, Fe2O3 $4H_2S$ —> $2FeS_2$ $3H_2O$ + H2. Iron in any form, however, will react with hydrogen sulfide to form ferrous sulfide. In reference to the cited experiment, as the rate of evolution of the hydrogen sulfide had been greatly increased artificially by the sodium lactate energy source over the normal rate in nature, the efficacy of this reaction in nature should be even greater.

In a similar experiment using a much smaller amount (2 g) of mud, most of the hydrogen sulfide produced escaped from the cell because it could not be retained as iron sulfide in the lesser quantity of mud. This experiment provided information on the significant rapid changes or variations in δ $s^{34}$ composition of the evolved hydrogen sulfide; changes in δ $s^{34}$ composition, in less than one hour, of more than 20 permil were evident. In fact, as mentioned above, it is evident from Figure 1 that not only does the evolved hydrogen sulfide vary in δ $s^{34}$ by more than 10 permil, but the mud contains disseminated sulfides that must vary from the original ratio value of 22.44 to less than 21.90 (almost 25 permil) for the additional sulfide formed during the experiment. Incidentally, the isotopic composition of the soluble sulfate in the sea water used in the experiment was 21.77, the same composition as sulfate in Long Island Sound where the anaerobic-bearing mud was obtained. Apparently, therefore, the sulfide that was forming naturally in Long Island Sound mud, with an average ratio of 22.44, was enriched in $s^{32}$ by about 3o permil.

In summary, therefore, the dual characteristics of (1) a relatively broad spread in δ $s^{34}$ values of sulfide sulfur and (2) an enrichment in $S^{32}$ in the sulfide over that of the source sulfate are quite suggestive of a biogenic origin for the sulfur. If the sulfate source is of marine origin, the sulfides may still exhibit positive δ $5^{34}$ compositions but still to a variable extent and an enrichment of as much as 20 permil in $s^{32}$ (Thode, Wanless, and Wallouch, 1954; Feeley and Kulp, 1957; Dessau, Jensen, and Nakai, 1962).

## SULFUR OF MAGMATIC HYDROTHERMAL ORIGIN

In contrast, numerous δ $s^{34}$ measurements of hypogene sulfides occurring in magmatic hydrothermal deposits, and

1. The generic name of sulfate reducers has at various times been Spirillum, *Microspira*, *Vibrio*, *Sporovibrio*, and *Desulfovibrio*. The latter name is now used most widely. In addition, a thermophilic variety Clostritium *nigrikans* is accepted as a sulfate reducer.

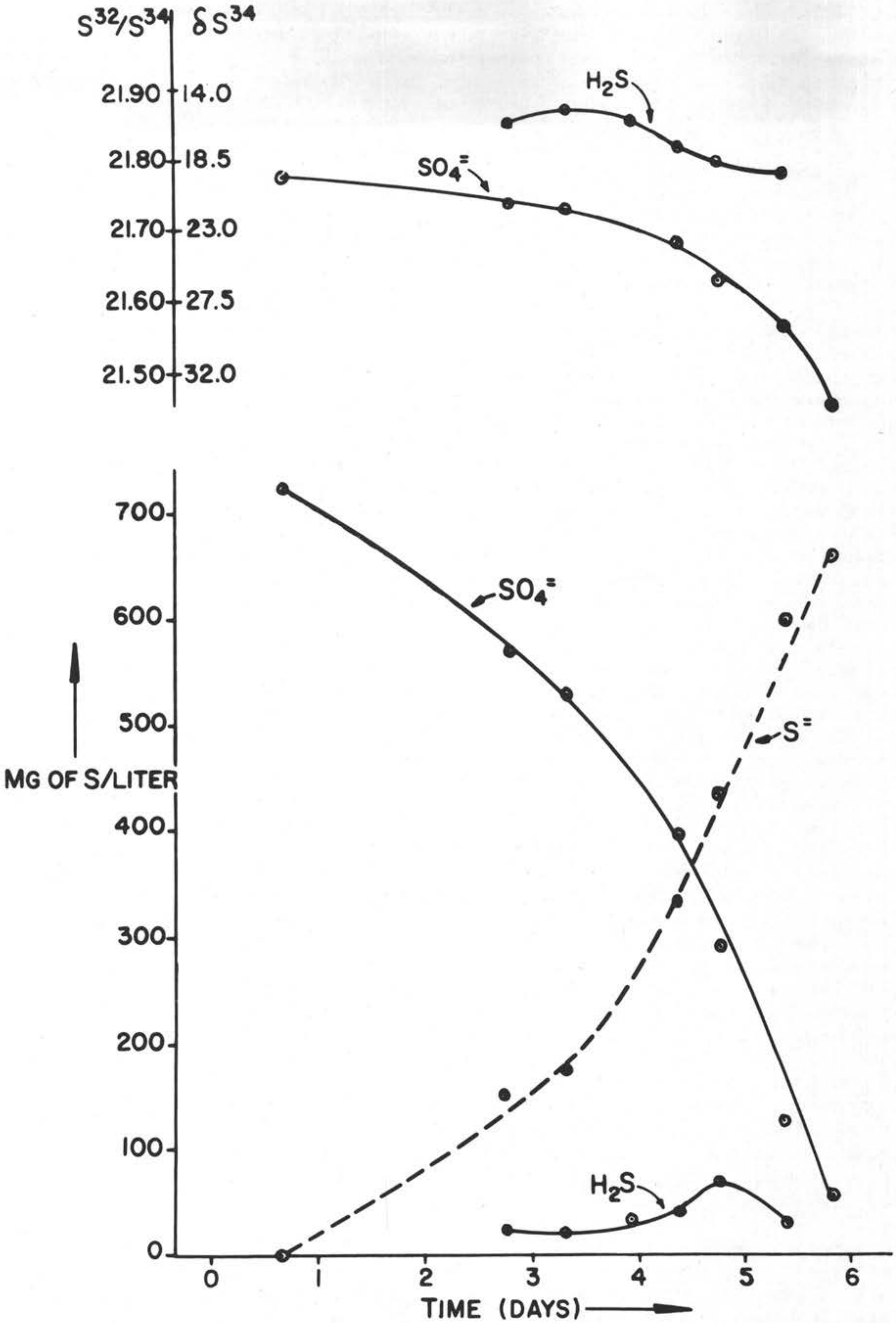


Figure 1

Laboratory experiment

even throughout a mining district, rarely vary in δ $S^{34}$ composition by more than ± 5 permil, and generally vary by even less. It is suggested that the reason for this is that magmatic hydrothermal solutions become more and more concentrated in a cupola zone during progessive crystallization of their host or parent magmas and the solutions become well mixed, resulting in a homogenization of what isotopic variations there may have been. Subsequently, with rapid escape of the mineralizing and ore solutions into fissures or fractures in the shattered roof pendants or surrounding rocks, very little, if any fractionation of the sulfur isotopes occurs. What fractionation does occur is almost invariably less than a few permil, as evident from the results obtained from δ $S^{34}$ studies of magmatic hydrothermal deposits.

## DISCUSSION OF RESULTS

A compilation of the *δ* $S^{34}$ results obtained from mineral specimens collected from uranium deposits in the Grants, Laguna, and Ambrosia Lake areas is given in Table I and shown graphically in Figure z. Information on the location and description of the specimens is given in Table i, with further data on the mineral species, $S^{32}/S^{34}$ ratio, δ $5^{34}$ composition, and whether the specimen was collected from ground barren of uranium (B) or associated with more than o.o1 percent $U_3O_8$. The collectors of samples are also indicated in Table 1 and Figure z.

In addition to the above deposits, δ $5^{34}$ results obtained from presumably magmatic hydrothermal uranium deposits are plotted in Figure **2** for comparison with the δ $S^{34}$ results of the sandstone-type uranium deposits.

The distinction between δ $S^{34}$ values for those deposits classified as Biogenic versus those classified as Magmatic Hydrothermal is graphically evident, as shown by Figure 2. Furthermore, sulfides from the laccolithic intrusives that form the La Sal Mountains near Moab, Utah, also exhibit the magmatic hydrothermal δ $S^{34}$ characteristics. One of the larger sandstone-type uranium districts of the Plateau, the Big Indian Wash district, about i 5 miles south of the La Sal Mountains, exhibits δ $5^{34}$ values highly but variably enriched in $S^{32}$; in fact, the $S^{32}/S^{34}$ ratio of almost i oo specimens there averages about 23.0 (Field).

An attempt to reconcile the geologic and mineralogic settings of sandstone-type uranium deposits with these isotopic results has given rise to the hypothesis (Jensen, 1958) that hydrogen sulfide gas, derived from sulfate-reducing bacteria, provided the reducing environment for the reduction and concentration of soluble hexavalent uranium to the relatively insoluble tetravalent form. The sulfate source was most likely predominantly connate water, and the energy source for the bacteria was provided by portions of the organic material existing in the nonmarine formations. The bleached effect of the sandstone where uranium and "red-beds" copper deposits have formed is the result of the reduction of ferric oxide to ferrous sulfide by the hydrogen sulfide according to the following reaction:

$$4H25\ FeS_2O_3 \longrightarrow zFeS_2\ \mathbf{H2} + 3H_2O$$

In a one-paragraph "nutshell," this is the hypothesis suggested by the mineralogic, geologic, and isotopic factors. Many **of** the ramifications of this hypothesis have been discussed elsewhere (Jensen, 1958; Field), but certain specific aspects that pertain more to the New Mexico deposits are dealt with in more detail in this paper.

The δ $S^{34}$ data of the New Mexico deposits listed in Table I are quite similar to δ $S^{34}$ results of many other Colorado Plateau sandstone-type uranium deposits. They are also quite comparable to δ $S^{34}$ results obtained from the Gas Hills and Shirley. Basin districts of Wyoming (Jensen, 1958; Field; Cheney). The Woodrow mine, however, at first glance does seem to present somewhat enigmatic δ $5^{34}$ results.

The raw culture cell experiment that has been described, and for which the results are shown in Figure 1, is quite helpful, however, in offering an explanation for the comparatively unusual δ $S^{34}$ results obtained for the Woodrow mine. Geological evidence suggests a limited source of anhydrite that overlies the Todilto Limestone in this collapse, breccia-pipe deposit. As the anaerobes in the breccia-pipe evolved hydrogen sulfide enriched in $S^{32}$, the remaining sulfate, depleted in $S^{32}$, became progressively enriched in $S^{34}$. As hydrogen sulfide continued to be evolved from the residual heavier sulfate, the later-formed sulfides also became progressively enriched in $5^{34}$, as is shown by the Woodrow mine results. This is also true for the later-formed sulfides in the biogenic experiment, shown diagrammatically in Figure . This is an example of the dovetailing relationships between field and laboratory studies, neither of which would be so significantly apparent were it not for the supporting corroboration of the other.

There does seem to be evidence that sulfides in the Ambrosia Lake area generally postdate the carbonaceous material, but some pyrite seems to be earlier (Granger et al., 1961). Certainly a more conclusive biogenic model could be presented if the time of uranium mineralization were known, but such conclusive information is not available. Nevertheless, it is possible to have not only several stages of bacterial production of hydrogen sulfide but possibly an almost continuous production. With such conditions the multiple paragenetic relationships of the sulfides observed is not a major problem at all.

Both syngenetic and diagenetic production of the reductant could have occurred with ease. But it is more difficult to infer the existence of viable anaerobes in the organic trash zones in, for example, the Morrison Formation during Early Cenozoic time due to the overlying thickness of Cretaceous sediments, not because of pressure (Zobell, 1953) but because of temperature conditions. Even with a normal geothermal gradient, for a sedimentary sequence, the higher temperatures would affect the viability of the anaerobes. It should be mentioned, however, that the *Clostridium* nigrif*icans* sulfate-reducing strain is thermophilic and does withstand temperatures in excess of 6o° C.

Be this as it may, it does seem possible that earlier-produced hydrogen sulfide may have remained where formed or have migrated to more porous zones, for example, in the West-water Canyon Sandstone Member where some of the reductant reacted with ferric iron to form preore ferrous sulfide, and the remainder awaited the arrival of uranium-bearing solutions, whatever their source or time of arrival, before reducing the soluble hexavalent uranium to the relatively insoluble tetravalent form. It might even be inferred that hydrogen **sulfide** produced in higher, lower-temperature horizons could have migrated to these deeper horizons instead of expecting earlier-formed hydrogen sulfide to remain dormant for long

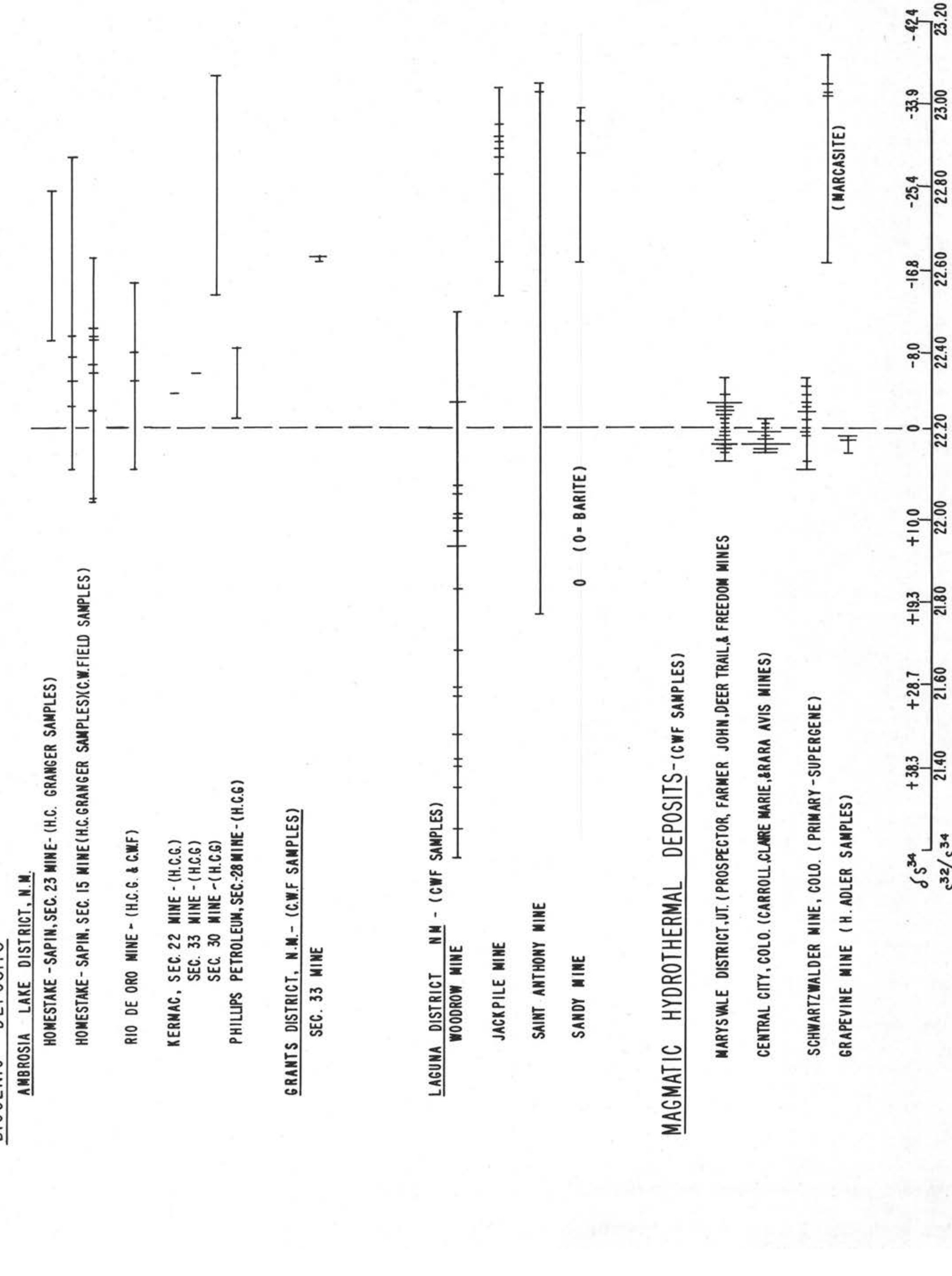


Figure 2

COMPARISON OF BIOGENIC AND HYDROTHERMAL SULFUR ISOTOPES

TABLE 1. SAMPLE DATA (C. W. Field specimens)

AMBROSIA LAKE AREA, NEW MEXICO

| SAMPLE | LOCATION AND DESCRIPTION | TYPE | MINERAL | $S^{32}/S^{34}$ | $\delta S^{34}$‰ |
|---|---|---|---|---|---|
| NM-1-58 | Section 15 mine, Ambrosia Lake area, McKinley County, New Mexico: 536-ft. level; pyrite with coffinite disseminated in Westwater Ss Mbr of the Morrison Fm (Jurassic) from fracture zone. | U | pyrite | 22.44 | − 9.8 |
| NM-2-58a | Section 15 mine: pyrite disseminated in "chocolate brown ore" from calc unit. | U | pyrite | 22.35 | − 5.8 |
| NM-2-58b | Section 15 mine: pyrite disseminated in brown ore of the calc unit. | U | pyrite | 22.37 | − 6.7 |
| NM-3-58a | Section 15 mine: pyrite from brown ore-green mudstone contact. | U | pyrite | 22.63 | −18.1 |
| NM-3-58b | Section 15 mine: finely disseminated pyrite in brown ore adjacent to contact. | U | pyrite | 22.43 | − 9.4 |
| NM-4-58 | Section 15 mine; disseminated pyrite in 6-in. clay gall from clayey ss unit. | B | pyrite | 22.46 | −10.7 |
| NM-5-58a | Section 15 mine: pyrite disseminated in fractured medium-grained ss unit. | U | pyrite | 22.26 | − 1.8 |
| NM-5-58b | Section 15 mine: pyrite disseminated in and coating fracture surfaces of ss unit. | U | pyrite | 22.04 | + 8.2 |
| NM-5-58c | Section 15 mine: pyrite coating fracture surfaces and disseminated in ss unit. | U | pyrite | 22.05 | − 7.7 |
| 2311-1 | Rio de Oro mine: D.D. Z 6/400, interval 380-390; pyrite disseminated in Westwater Ss. | B | pyrite | 22.12 | + 4.5 |
| 2504 | Rio de Oro mine: pyrite disseminated in "chocolate brown ore". | U | pyrite | 22.57 | −15.5 |
| | GRANTS DISTRICT, NEW MEXICO | | | | |
| SRA-1 | Faith mine, Grants district, McKinley County, New Mexico: pyrite and barite with uraninite from the Todilto Ls (Jurassic). | U | pyrite<br>barite | 22.84<br>21.86 | −27.2<br>+16.5 |
| NM-7-58a | Section 33 mine, Grants district, Valencia County, New Mexico: 6880 area; pyrite veinlets in the Todilto Ls. | B | pyrite | 22.63 | −18.1 |
| NM-7-58b | Section 33 mine: 6880 area; pyrite veinlets in the Todilto Ls. | B | pyrite | 22.62 | −17.7 |
| NM-7-58C | Section 33 mine: 6880 area; pyrite veinlets in the Todilto Ls. | B | pyrite | 22.63 | −18.1 |
| | LAGUNA DISTRICT, NEW MEXICO | | | | |
| 1870 | Woodrow mine, Laguna district, Valencia County, New Mexico: marcasite and coffinite from brecciated pipe containing fragments of the Jackpile ss and Recapture Sh members of the Morrison Fm (Jurassic). | U | marcasite | 21.93 | +13.2 |
| W-100/10-1 | Woodrow mine: 20-ft. level, near center of pipe; pyrite impregnating ss and partly replacing the detritus. | U | pyrite | 21.68 | +24.9 |
| W-100/8-1 | Woodrow mine: 35-ft. level, from ring fault; pyrite-coffinite mixture with other sulfides and veined by gypsum. | U | pyrite | 22.00 | +10.0 |
| W-100/8-2 | Woodrow mine: 35-ft. level, from ring fault; rich sulfide-coffinite ore in ss. | U | pyrite-marcasite | 21.59 | +29.2 |
| W-100/8-3 | Woodrow mine: 35-ft. level outside ring fault; rich sulfide-coffinite ore replacing ss detritus. | | pyrite-marcasite | 22.28 | − 2.7 |
| C-55-26A | Woodrow mine: 50-ft. level, near ring fault; rich sulfide-coffinite ore. | U | pyrite | 22.50 | −12.4 |
| NM-14-58 | Woodrow mine: 50-60-ft. level; rich ore with massive sulfides in breccia. | U | pyrite-marcasite | 22.28 | − 2.7 |
| NM-13-58a | Woodrow mine: 100-ft. level; pyrite disseminated in sandy sh. | B | pyrite | 21.18 | +49.1 |
| NM-13-58b | Woodrow mine: 100-ft. level; pyrite disseminated in sandy sh. | B | pyrite | 21.42 | +37.4 |

TABLE 1. SAMPLE DATA (C. W. Field specimens) (continued)

| SAMPLE | LOCATION AND DESCRIPTION | TYPE | MINERAL | $S^{32}/S^{34}$ | $\delta S^{34}‰$ |
|---|---|---|---|---|---|
| W-200-5 | Woodrow mine: 200-ft. level, ring fault boundary, pipe side; pyrite disseminated in silty mudstone breccia. | B | pyrite | 21.93 | +13.2 |
| NM-10-58a | Jackpile mine: NW end of pit; pyrite replacing carbonaceous matter in basal units of the Dakota Sandstone (Cretaceous). | B | pyrite | 23.04 | −35.6 |
| NM-10-58b | Jackpile mine: NW end of pit; pyrite replacing carbonaceous matter in ss. | B | pyrite | 22.83 | −26.7 |
| NM-10-58c | Jackpile mine: NW end of pit; pyrite replacing carbonaceous matter in ss. | B | pyrite | 22.95 | −31.8 |
| NM-11-58a | Jackpile mine: N end of pit; pyrite disseminated and replacing carbonaceous matter in ss. | U | pyrite | 22.92 | −30.5 |
| NM-11-58b | Jackpile mine: N end of pit; pyrite replacing carbonaceous matter in ss. | U | pyrite | 22.91 | −30.1 |
| NM-11-58c | Jackpile mine: N end of pit; pyrite replacing carbonaceous matter in ss. | U | pyrite | 22.89 | −29.3 |
| NM-11-58d | Jackpile mine: N end of pit; pyrite replacing carbonaceous matter in ss. | U | pyrite | 22.87 | −28.4 |
| $Jp\text{-}n_1$ | Jackpile mine: center of pit; pyrite disseminated in coarse-grained arkosic Jackpile ss (Jurassic). | U | pyrite | 22.62 | −17.7 |
| NM-13-58c | Woodrow mine: 100-ft. level; pyrite disseminated in sandy sh. | B | pyrite | 21.40 | +38.3 |
| NM-13-58d | Woodrow mine: 100 ft. level; pyrite disseminated in sandy sh. | B | pyrite | 21.25 | +45.6 |
| W-100-2 | Woodrow mine: 100-ft. level, from pipe; pyrite disseminated in mudstone fragment. | U | pyrite | 21.83 | +17.9 |
| W-100-1 | Woodrow mine: 100-ft. level, 3 ft. from ring fault; massive sulfide formed by complete replacement of ss. | U | pyrite-marcasite | 22.08 | + 6.3 |
| W-100-X | Woodrow mine: 108-ft. level, center of pipe; sulfides disseminated in mudstone. | U | pyrite | 21.97 | +11.4 |
| W-200/3-4 | Woodrow mine: 175-ft. level, center of pipe; pyrite-carbonate cementing mudstone breccia. | U | pyrite | 22.06 | + 7.3 |
| W-200/3-3 | Woodrow mine: 175-ft. level, center of pipe; vuggy carbonate-mudstone-sulfide mixture. | B | pyrite-marcasite | 21.57 | +30.2 |
| W-200-2 | Woodrow mine: 200-ft. level, center of pipe; pyrite disseminated in coarse arkosic ss. | U | pyrite | 22.01 | + 9.5 |
| W-200-3 | Woodrow mine: 200-ft. level, center of pipe; pyrite-bearing mudstone breccia. | U | pyrite | 21.55 | +31.1 |
| W-200-4 | Woodrow mine: 200-ft. level, near ring fault; pyrite disseminated in dark brown ss. | U | pyrite | 21.48 | +34.4 |
| J-230-A3 | Jackpile mine: S end of N ore body; pyrite disseminated in uraniferous ss. | U | pyrite | 22.54 | −14.2 |
| SA-6B | St. Anthony mine: pyrite disseminated in gray rim of zoned mud gall having red core from the Jackpile ss. | U | pyrite | 21.77 | +20.7 |
| SA-5 | St. Anthony mine: pyrite disseminated in uraninite and enclosing mudstone host. | U | pyrite | 23.05 | −36.0 |
| SA-3 | St. Anthony mine: pyrite disseminated in rich uraninite ore. | U | pyrite | 23.03 | −35.2 |
| C-55-27 | Sandy mine: Pyrrhotite band in lime-silicate rock formed by contact effect of diabase sill on uraniferous Todilto Ls (Jurassic) inclusion. | U | pyrrhotite | 22.88 | −28.8 |
| S-2 | Sandy mine: pyrite disseminated in Todilto Ls 5 ft. above uranium deposit in Entrada Ss. | B | pyrite | 22.99 | −33.5 |
| S-5 | Sandy mine: pyrite-uraninite concretion in the Entrada Ss (Jurassic). | U | pyrite | 22.96 | −32.2 |
| S-6 | Sandy mine: pyrite and barite from the Todilto Ls 5 ft. above a small uranium deposit in the Entrada Ss. | B | pyrite<br>barite | 22.62<br>21.84 | −17.7<br>+17.4 |

TABLE 1 (continued)

SAMPLE DATA (H. C. Granger specimens)
AMBROSIA LAKE AREA, NEW MEXICO

| SAMPLE | LOCATION AND DESCRIPTION | MINERAL | $\delta S^{34}‰$ |
|---|---|---|---|
| 11 G 58 | Rio de Oro mine, Ambrosia Lake area, McKinley County, New Mexico: impregnation and fracture filling in mudstone gall. | pyrite | − 7.9 |
| 59 ES 59 | Rio de Oro mine, impregnated layer in gray limy sandstone. | pyrite | − 5.0 |
| 276 59 | Homestake–Sapin Partners, Sec. 15 mine: pyrite from fracture that cuts black carbonaceous uranium ore layer. | pyrite | −28.4 |
| 31 G 59 | Homestake–Sapin Partenrs, Sec. 15 mine: pyrite and minor barite from fracture. | pyrite | − 9.8 |
| 32 G 59 | Homestake–Sapin Partners, Sec. 15 mine: impregnating and filling fracture in limestone nodules in a mudstone layer. | pyrite | − 2.3 |
| 33 G 59 | Homestake–Sapin Partners, Sec. 15 mine: very fine-grained impregnation and fracture fillings in a gray limy sandstone layer immediately above the mudstone layer noted in sample 32 G 59. | pyrite | + 4.5 |
| 7 G 60 | Homestake–Sapin Partners, Sec. 15 mine: disseminated in a thin layer lateral to a small fault, no pyrite in fault. | pyrite | − 5.0 |
| 42 G 59a | Homestake–Sapin Partners, Sec. 15 mine: fills fracture that cuts black carbonaceous uranium ore layer. | pyrite, possibly some marcasite | − 7.6 |
| 2 G 60 | Kermac Sec. 22 mine: thin pyrite-impregnated layer at base of mudstone that overlies Westwater Canyon Member. | pyrite | − 3.7 |
| 15 G 60 | Kermac Sec. 33 mine: fracture filling. | pyrite | − 5.7 |
| 1 F 60 | Kermac Sec. 30 mine: impregnated sandstone. | pyrite | −13.9 |
| 2 F 60 | Kermac Sec. 30 mine: fractures in coalified and silicified fossil tree. | pyrite | −36.7 |
| 1 ES 60 | Phillips Petroleum Co., Sec. 28 mine: surface coating in fault. | pyrite and marcasite(?) | − 8.6 |
| 2 ES 60 | Phillips Petroleum Co., Sec. 28 mine: impregnation in mudstone galls. | pyrite | − 0.9 |
| 11 G 60 | Homestake–Sapin Partners, Sec. 23 mine: from fracture where it intersects the top of a black carbonaceous uranium ore layer. | pyrite | −24.9 |
| 12 G 60 | Homestake–Sapin Partners Sec. 23 mine: fracture filling. | pyrite | − 9.1 |

periods of time. It might be mentioned, however, that the same biogenically produced gas has remained associated with sour crude oils at even greater depths for longer periods of time.

A rather similar feature of the Shirley Basin district deposits with the Ambrosia Lake deposits that is not commonly found in other sandstone-type uranium deposits is the elongate, sinuous interface between unaltered sandstones and altered or oxidized sandstone beds (Granger et al., Harshman, 1962). Much of the ore being mined at Ambrosia occurs associated with these interfaces, which suggests that redistributing ground-water solutions, transporting uranium, may have formed these ore deposits and partially changed the pre-existing mineral assemblages in what is now the altered, variegated colored sandstone.

In the Ambrosia Lake area these (sometimes stacked) redistributed deposits contain postfault ore, but generally contain very little organic material (Granger et al.). It is suggested that these favorable stratigraphically and structurally controlled sites would also be suitable traps for the accumulation of hydrogen sulfide, produced elsewhere where organic matter existed, which, of course, would be the effective reductant that concentrated the uranium in these traps.

Incidentally, the altered sands offer a potentially promising $\delta O^{18}$ study, whereby additional evidence might be acquired about the source of the altering solutions. Pre-existing pyrite in these sands has been oxidized to ferric oxide by these solutions, the uranium minerals at the interface contain oxygen, the kaolinized, arkosic sands contain oxygen derived from the altering solutions, and calcite is not uncommon, especially at the interface. A $\delta O^{18}$ study of these oxygen-bearing minerals might provide substantial information about the source of the altering solutions and possibly also, therefore, the source of the uranium. In other words, will oxygen isotopes assist in determining whether the uranium is derived by renewed introduction or by the redistribution of pre-existing primary uranium?

In conclusion, it should be obvious that no attempt is being made to indicate that stable isotopic studies and the agency of biogenically produced hydrogen sulfide provide the genetic panacea for the origin of sandstone-type uranium deposits. Nevertheless, the $\delta S^{34}$ composition of sulfides associated with sandstone-type uranium deposits strongly suggests that anaerobically produced hydrogen sulfide does play an important role in the localization of these deposits.

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# *Ore Processes*

R. A. LAVERTY, W. R. ASHWILL, W. L. CHENOWETH, AND D. L. NORTON

## ABSTRACT

Considerable agreement has been reached among the authors as to the precipitation, enrichment, and protection of the uranium ores in the Grants region, but considerable disagreement remains as to the source of ore-bearing solutions and the methods of solution transport inherent in the various sources. This reflects the amount of data available, which is abundant at the site of deposition but increasingly rare as possible sources are approached.

The ore-forming process was long and complicated, and it appears probable that sedimentary, tectonic, volcanic, and meteoric activity affected the ore or its environment at different times during ore formation. The resulting melange of contradictory evidence is classified under the headings of lithology, structure, igneous effects, and solution effects. Each of the processes affecting the location of ore—the various sources of solutions, solution transport, precipitation, enrichment, and protection—is treated separately by considering how the applicable parts of the four classes of data tend to support or refute the particular process.

The conclusions reached are that the source of uranium may have been volcanic, hydrothermal, syngenetic, or a combination of all three. Ground water formed the major part of the ore-bearing solutions, but hydrothermal and volcanic additives improved the effectiveness of the solutions and possibly added uranium to them. Lignitic detritus and derivatives precipitated most of the ore, but hydrogen sulfide probably aided the process. Enrichment of the ore was controlled by fracturing related to tectonic and igneous activity. Protection of the precipitants during their emplacement and subsequently until the arrival of ore-bearing solutions explains the narrow stratigraphic range of the large ore deposits, which were protected by high water tables, postore calcite, and the stability of urano-organic complexes.

## INTRODUCTION

The complete process resulting in a presently mineable ore deposit has several phases, including source of solutions, solution transport, precipitation, enrichment, and protection.

The description of the ore process starts with how and where the uranium entered the solution that bore it to its present location. The next step is to define the paths which the solutions used and the reasons for the pressure gradient down which they moved. There is evidence that the ores at Grants were precipitated by a chemical reaction with specific substances rather than by a change in pressure or temperature. The nature, source, and emplacement of the ore precipitant must be defined, and the reaction and locale of the precipitation determined. Because some of the richest ore may be younger than the rest, the source of the enriching uranium and the mechanism of its emplacement need to be defined. To be mineable today, the deposits must have remained in environments in which they were protected from leaching and erosion until recent times.

We gratefully acknowledge helpful discussions with the many geologists working in the area and the data we have received from them over the past several years. We appreciate the critical review of parts of the paper by R. T. Russell and S. Ralph Austin.

## SOURCE OF SOLUTIONS

### HYDROTHERMAL THEORY

A hydrothermal source for uranium-bearing solutions has been proposed by many workers, including Hess (1922), Kerr (1958), and McKelvey, Everhart, and Garrels (1955). Possible hydrothermal sources in the Grants district are related to the Zuni uplift, where fluorite veins occur, or to the Mount Taylor volcanic field, in which the only hydrothermal (?) deposits are nonradioactive travertine beds overlying fossil springs related to the San Rafael fault (*Thaden and Santos*, this memoir). The axis of the Mount Taylor field crosses the Zuni Mountains near the area where the fluorite mines are found.

Most objections to a hydrothermal source emphasize the lack of mineralized feeder structures beneath uranium deposits. The usual answer is that hydrothermal solutions joined the ground water, and the resulting solution, being more diluted, traveled long distances laterally in the sediments without leaving many traces. It might also be pointed out that even in vertical veins in igneous rock, epithermal, base-metal deposits commonly lose their identity by pinching out downward into a tight fracture filled with a fraction of an inch of quartz. These tight, quartz-filled fractures below ore show no differences from thousands of tight, quartz-filled fractures many miles from any observable metallization.

Studies of thermal waters connected with volcanism (for example, White, 1957; Zies, 1929) show that in many instances hydrothermal activity does not begin until late in the volcanic process and persists for a long time. Further, White's work suggests that volcanic fluids account for less than five percent of the waters issuing from thermal springs of volcanic origin. The other 95 percent consists of connate and meteoric waters, which are suggested as a base for uranium deposition by the wide lateral spread of deposits in a narrow stratigraphic range. To make this base sufficiently effective may require added reagents, and volcanic additives are close at hand.

### LITHOLOGY

Highly permeable units in the stratigraphic sequence are the Meseta Blanca Member of the Yeso, San Andres, Wingate, Entrada, Bluff, Dakota, Gallup, Dalton, and Point Lookout. Nearly impermeable units are the silty and shaly parts of the Chinle, Summerville, Recapture, Brushy Basin, Mancos, and Mesaverde. Units of medium permeability are the Abo, Sonsela sandstone bed of the Chinle, Todilto, Recapture (sandy part), Westwater Canyon, Brushy Basin sands (including the local units of Poison Canyon and Jackpile), and the Tres Hermanos; all the major ore hosts are in-

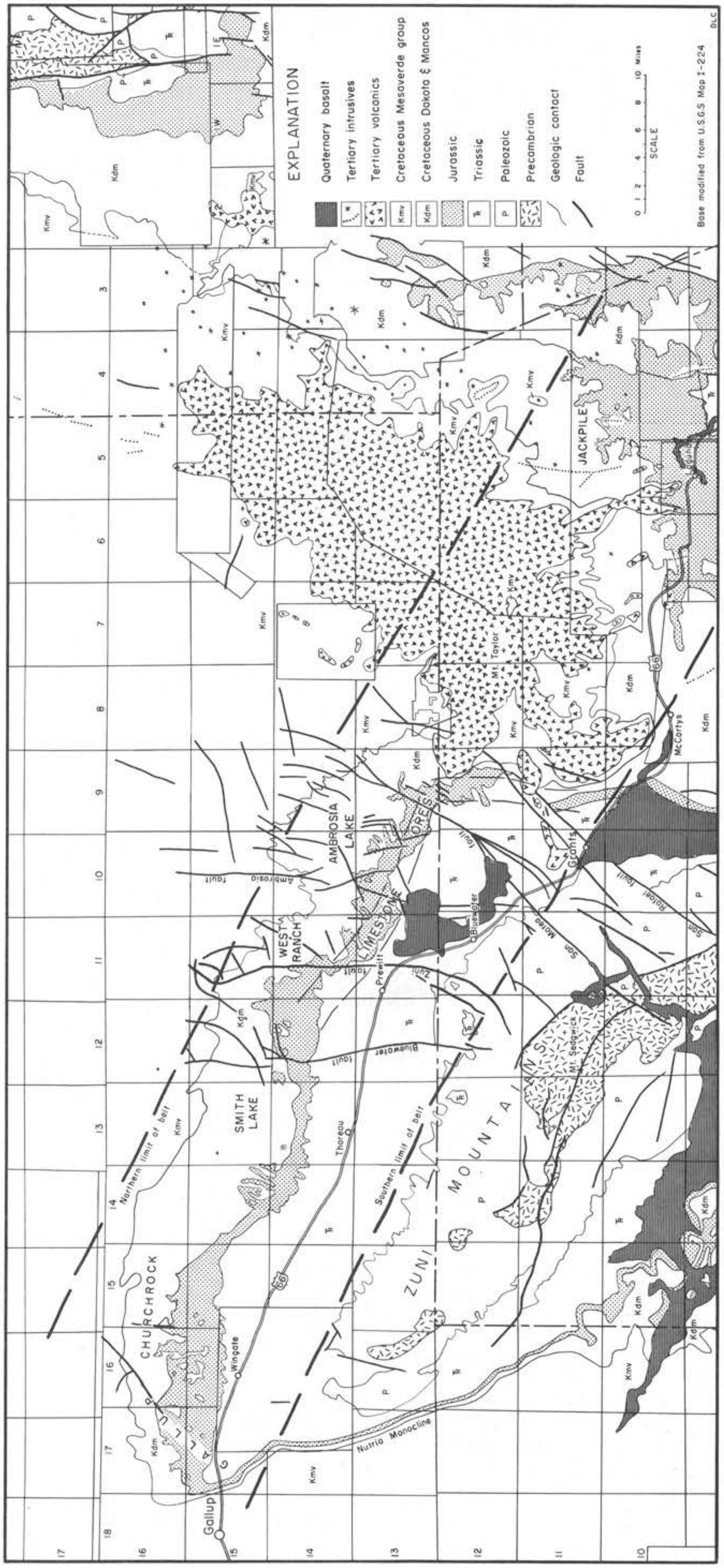


Figure 1

GEOLOGIC MAP OF THE GRANTS REGION, SHOWING THE GRANTS MINERAL BELT, THE LIMESTONE ORE TREND, AND MINING AREAS eluded in this group. Hydrothermal solutions can explain the geographic coincidence of ore in the Dakota, Morrison, and Todilto by supplying ore-bearing solutions to all formations in the district through tension fractures with subsequent movement through the permeable beds. Only those permeable beds containing effective precipitants would then be host to ore.

## STRUCTURE

Fault control of the ore district boundaries and many ore bodies in different strata is to be expected if a hydrothermal source is postulated. The lack of uranium in the principal fracture systems corresponds to experience in many metal mining districts.

Although almost all the pipe structures in the Laguna district have been explained by ground-water dissolution of the underlying Todilto—perhaps explaining their lack of ore—the presence of so many igneous plugs east of Mount Taylor suggests a cryptovolcanic origin of the few ore-bearing pipes to some (Perry, 1961; Gableman, 1957). If the Woodrow pipe is related to the Mount Taylor plugs, then its ore is Miocene (?) or later and might imply a similar age for the rest of the ore in the district. It also implies that the plugs along the eastern side of Mount Taylor are older than the diabase dikes, one of which cuts the Jackpile ore body. If the Woodrow pipe has the same pre-Dakota age as the other pipes in the district, then any postulated igneous activity connected with it would be related to the volcanism producing the ash in the Brushy Basin *(Wylie,* this memoir).

## IGNEOUS EFFECTS

The outcrop of the central core of the Laramide (?) Zuni uplift is composed of Precambrian granites and metamorphics, not Tertiary granite. The observable igneous activity in the Grants district is concentrated in the Tertiary Mount Taylor volcanic field, which locally intrudes the eastern tip of the Zuni uplift almost perpendicularly to its axis. If there were magma under the Zuni uplift, we might expect most evidence of hydrothermal activity to occur on the steeper southwestern side opposite the Grants district.

The location of a volcano which erupted perhaps 15 cubic miles of lava and pyroclastics between the two richest areas of the Grants uranium region warrants some consideration as the source of changes in the rocks which overlie its vent. The changes in these rocks at their contacts with the eruptives are slight and probably are the result of the rapid chilling of such narrow necks and thin flows. Volatiles from these fluid lavas would have little tendency to enter the sediments because of easier access to the atmosphere through the vents and from the upper surfaces of flows.

There still remains the possibility of later fluid volcanic additives to ground waters, and this leads to consideration of the thermal gradient. If hydrothermal waters in uranium deposits follow the same pattern as in base-metal districts, the ore episode occupied only a short interval somewhere in the over-all range of hydrothermal activity. The solutions preceding the ore would raise the temperature of the enclosing rock and permit the later ore solutions to flow down a low-temperature gradient. Deposition would then occur as a result of reaction with precipitating agents rather than result from chilling of the solutions.

Perhaps the main difference between epithermal base-metal veins and uranium deposits is one of environment. The vein solutions rise through hard rock containing little connate water. They are not diluted, and they are confined to a vein network of limited extent in relatively impermeable rock. One common result of undiluted solutions acting on limited volumes of rocks is intense alteration—sericitization, propylitization, argillization.

The alteration in Plateau uranium deposits depended upon diluted, cooler solutions reacting with large volumes of rock, and produced only minor silica, feldspar, anatase, kaolin, and pyrite from the destruction of sanidine, ilmenite, and magnetite, but no sericitization or propylitization.

The counterpart of pervasive, low-intensity alteration would be dispersed uranium minerals in the favorable beds containing large quantities of scattered organic matter. If the same beds had not contained concentrated masses of organic matter, it is doubtful that ore bodies of the present size would have been formed.

Sulfur isotope ratios at Grants show a larger spread than commonly occurs in base-metal sulfides in veins (Jensen, Field, and Nakai, 196o). In vein deposits, however, the sulfide *is* the ore and is little diluted by sulfur from the host rock. In the Grants uranium deposits, a great deal of pyrite is not gangue deposited from the ore-bearing solution. The deposit is not insulated from the country rock but permeates it, filling interstices between sand grains and replacing limestones and organic matter. The sulfides, mainly pyrite and marcasite, which were formed in the host rocks during diagenesis were engulfed. Since the deposits occur in fairly permeable aquifers, they have only moderate protection against postore additions of iron sulfides to the ore bodies. The net result is that the spread of $5^{32}/S^{34}$ ratios measures the environment of the ore deposits but does not measure the characteristics of the ore-bearing solutions.

The massive pyrite occurring at the Woodrow pipe *(Wylie,* this memoir) is a different problem. It is typical of hydrothermal deposits, except that it has a wide spread in $S^{32}/S^{34}$ ratios. In this instance, the pyrite is definitely gangue and sometimes ore, since some large crystals contain as much as one percent $U_3O_8$ as particles of submicroscopic size. To explain the $S^{32}/S^{34}$ ratios, we cite the work of White, which suggests that volcanic solutions are so diluted by connate waters that thermal springs contain less than five percent volcanic additives. Sulfate-bearing ground waters, which permeate many of the sediments of the Grants region, would then contribute a wide range of quantities of $S^{32}$ and $S^{34}$ to the ore-bearing solution.

Vanadium, molybdenum, iron, sulfur, selenium, and fluorine occur in greater quantities in the ore than in barren parts of the host rocks at Grants. With the exception of vanadium, these elements, called *extrinsic* by Shoemaker et al. (1959), are common in hydrothermal deposits.

In the mines in the Morrison at Ambrosia Lake, almost all the uranium is contained in coffinite and in organic complexes, while at Laguna, uraninite is added to this assemblage *(Granger*, this memoir). In the Todilto, the unoxidized ore bodies have uranium contained in uraninite, with lesser amounts in uraninite-fluorite intergrowths and in organic complexes (Laverty and Gross, 1958). Pyrite and/or marcasite occur with all Grants uranium (Granger, this memoir), but at the Woodrow pipe massive iron sulfides are a major gangue mineral *(Wylie,* this memoir). The variations in ore mineralogy at Grants probably reflect variations in the host sediments, but variations in ore mineralogy are common in hydro-thermal veins even where there is little variation in wall rocks.

The regional alteration described by Austin is far more pervasive than the paleo-outcrop kaolinization described by Leopold (1943). The feldspar-quartz-anatase-kaolin alteration *(Austin,* this memoir) has been found at depths of 2000 feet and in all colors of Westwater sandstones. Although the pervasiveness of the alteration indicates a relation to ground water, it seems probable that the active reagents came from humic and/or hydrothermal sources. The qualitative intensification of this alteration near ore could be ascribed either to the ore-bearing solutions or to organic acids related to the emplacement of large quantities of the precipitant. Heald (1955) has shown that humic solutions are effective solvents of sand grains.

The local alteration in the Todilto does not require hydrothermal solutions, but it does require something more effective than the ground waters presently oxidizing the deposits. Nothing resembling the recrystallized ore-bearing zones can be observed taking place today. Fluoritization of the Todilto does not require hydrothermal action either, but fluorite veins occur in the Zuni Mountains, and the late purple coloration of the brecciated veins might possibly be interpreted as radiation damage. No radiation can now be detected, however, so the radiation damage postulate rests on the assumption of subsequent flushing of the vein by nonradioactive solutions or on damage by short-lived daughters below radium in the decay series. Fluoritization in the Todilto is most intense in a zone parallel to and less than three miles west of the San Rafael fault.

## ASH LEACH THEORY

### Source of Ash

The observation that nearly all sandstone-type deposits are overlain by and intertongue with bentonitic clays and silts led to the proposal that these altered ash beds, by devitrification and/or weathering, contributed the uranium for the deposits now being mined. Waters and Granger (1953), in one of the most perceptive and widely misquoted papers on Plateau geology, examined the ash-leach theory and found two possible objections. They doubted that metallic ions, in contrast to the alkali ions, would escape adsorption by montmorillonite in the source bed, and they felt that such a broad source should yield broader and more continuous deposits than are the rule on the Colorado Plateau. Although Waters and Granger may have had second thoughts in the succeeding years, they proposed (1953) hydrothermal reactivation of ground-water circulation as the immediate process responsible for Plateau deposits.

Waters and Granger noted the early-to-intermediate silicification of the ore-bearing sandstones of the Colorado Plateau and the later, but still preore, solution of both silica overgrowths and detrital quartz grains in the sandstone ore bodies. They attributed the silicification to the excess derived from devitrification and the solution to activity of the ore solutions.

Interpretation of later work makes it desirable to modify these conclusions. Austin's (this memoir) description of regional quartz-feldspar-anatase-kaolin alteration leads to the conclusion that the silicification resulted from the devitrification of small, thin lenses of ash-bearing clay within the host sandstones and from the kaolinization of feldspars. We deduce this not only from Austin's data but from the observation that intense silicification is seldom the main alteration in the Westwater, and where it predominates, the silicified zone is barren. It appears that silica has been transferred only from the borders of the ash beds, not from the main mass. Waters and Granger noted in other parts of the Plateau a phenomenon that is ordinary at Grants; namely, externally introduced alteration, such as uranium minerals, commonly penetrates only a fraction of an inch into bentonitic clay seams and galls. It appears reasonable that transmission in the opposite direction would be equally difficult. If the Brushy Basin at Grants had been leached of all its excess silica, the underlying West-water should be more silicified than is now observed.

Nevertheless, Waters and Granger appear to be on firm ground when they concluded from the amount of water-borne pyroclastics included in the ore-bearing Triassic and Jurassic strata on the Colorado Plateau that their source areas were subject to large ash falls, and that this offers a ready explanation of the occurrence of almost all the Plateau ores in a restricted stratigraphic sequence. The widespread occurrence of ash in the Brushy Basin suggests volcanic action throughout the area of deposition, not just in the source area.

Denson, Bachman, and Zeller (1959) proposed a tuffaceous source for uranium in lignite in South Dakota. They advocated leaching of the ash during the present weathering cycle. In contrast to postulation of a general expulsion of uranium from the tuff, they pointed out the relation of uraniferous lignite to fractures which developed during the present uplift and which cut both lignite and overlying tuff. At Grants there are two erosion intervals during which uranium may have been leached from the Brushy Basin and deposited in the Westwater and Todilto, one pre-Dakota and the other Tertiary.

Garrels (1957) also advocated a tuffaceous source for Colorado Plateau uranium. He used the Late Cretaceous lead-uranium ages of Colorado Plateau ores to place mineralization in a deep-seated environment at a time when the Morrison was buried under the Cretaceous. He described the solutions which may transport uranium, but he did not consider the mechanism of detachment from the clay beds. He noted the discontinuous nature of uranium deposits, but classed this under the heading of puzzling aspects yet to be resolved.

Some deposits in the Brushy Basin in Montezuma Canyon, Utah, described by H. B. Wood (personal communication) as being probably derived from overlying ash, are what would be expected from such a source. They are small, oxidized, siliceous, and without calcite.

### Lithology and Structure

Derivation of ore in the Dakota, Brushy Basin, Westwater, and Todilto from the Brushy Basin shales requires downward leaching along faults to move uranium into the lower Westwater and Todilto, or into the Dakota where steep dips place it at a lower elevation than some of the Brushy Basin which is now eroded.

Deposition of uranium in the three major units—Todilto, Westwater, and Brushy Basin—is required to take place during the present or pre-Dakota erosion cycles to release uranium from the bentonite by weathering. On the basis of present tonnages, perhaps 99 percent of the solutions went into the Westwater and Bluff and one percent entered the Todilto. Without the faults, it is difficult to see how the solutions could pass the Summerville or how they could enter the weathered Brushy Basin surface deep enough to leach uranium and still have sufficient flow to gain the Todilto without being drained into the permeable Bluff and Westwater.

The location of the Ambrosia Lake area on a horst does not support the deposition of uranium ore bodies from ground waters during the present oxidation cycle if the source lies in the Zuni area or beyond it to the south. The normal gradient would lead north-flowing waters to avoid the horst. Mount Taylor and the limited Jurassic outcrop would provide the only surface water flowing directly to the ore areas on the horst.

Concentration of ore in the Woodrow pipe is at least possible by theories depending on ground water. It is located on a minor fracture which could channel uranium and iron-bearing ground waters into the pipe. Anaerobic bacteria in the Todilto could generate hydrogen sulfide to rise along the pipe. When the two solutions met, the resulting reaction would form uraninite and/or coffinite and pyrite and/or marcasite. A similar mechanism is postulated by Jensen, Field, and Nakai to account for the extreme spread in $S^{32}/S^{34}$ ratios found in samples from this pipe.

Solution Effects

The uraninite-fluorite mineralization and the recrystallization in the Todilto are difficult to explain by ash leachates. Siliceous solutions acting on limestone should form siliceous minerals rather than recrystallized calcite. An example is seen in present oxidation in which the calcium-uranium silicate, uranophane, is formed. Fluorine might well be a constituent of an ash leachate, but a large reducing potential would be required to form uraninite from such an oxygen-charged solution.

## GRANITE LEACH THEORY

Granite leach theorists postulate syngenetic uranium derived from the source areas of the ore-bearing sediments, either in detrital minerals or in solution in the waters depositing these formations, combined with additions from any associated pyroclastics. Gruner (1956) proposed such a source in Wyoming for the uranium to be concentrated by his multiple migration-accretion process; Noble (196o) and Zitting et al. (1957) proposed such a source for the deposits at Grants.

Zitting et al. also proposed to retain the syngenetic uranium in the Westwater by entrapment in a shallow, closed basin at the time of deposition. The dispersed uranium updip from the present deposits would then be moved downdip during the present erosion cycle by meteoric waters to the site of present deposits where it would be precipitated by humic acids derived from oxidation of oil spilled from its reservoir under the Ambrosia Lake dome. They gave no reference to substantiate the process by which oxidation produces humic acid from petroleum, nor did they explain the absence of the usual evaporites expected from deposition of sediments in a closed basin.

Noble, on the other hand, proposed to move saline, uranium-bearing connate waters up the sides of the San Juan Basin by compaction of the clays and silts from the weight of the overlying Cretaceous and from tectonic compression. Precipitation would have come when the pH of the saline waters was reduced by encountering fresh meteoric water or when decreasing pressure allowed carbon dioxide to exsolve, thus destroying the carbonate complexes on which the uranium depended for solution. He did not consider the difficulties in removing metallic ions from the bentonite source bed important, and he stated that adsorption on clays or organic matter may trigger the precipitation processes noted above.

Perry (this memoir) proposes secretion of uranium by the algae which formed some reeflike structures seen in the ore lenses.

Uranium was included in the several strata, both Jurassic and Cretaceous, by deposition from a more or less continuous supply of uranium-bearing detrital grains or surface waters during most of Jurassic time, with perhaps a lessening of the supply during Cretaceous time. Such a supply would depend on an uplifted mass of igneous or other uraniferous rocks in the presumed Mogollon highland as the source of the sediments. The low-grade distribution throughout the sediments could then be concentrated into ore deposits in strata where suitable masses of precipitants had been emplaced, but not in leachable formations like the Bluff. The uranium in the impermeable strata would remain dispersed. The location and trend of the Grants mineral belt parallel to and ahead of the erosion front would be expected as the highlands were uplifted.

A syngenetic source for the uranium in the Todilto would appear especially difficult. The limestone and gypsum are more than 95 percent chemical or organic and are largely evaporites; yet the formation is not anomalously radioactive as a whole. Uranium carried in solution or as detritals of unknown type would have to be deposited on entry of the stream into the marine(?) waters. Under such conditions ore would not be expected to deposit in faulted anticlines, although algal reefs (Perry, this memoir) might be sites of deposition. It would appear more logical to derive the Todilto deposits by leaching from those in the Morrison which occupy the same fracture zones, or to precipitate the uranium from hydrothermal solutions.

Solution Effects

The recrystallized limestone, uraninite veinlet fillings, replacement textures and zones of uraninite-fluorite intergrowths found in the Todilto are not typical syngenetic structures and textures. Neither are these the minerals and textures expected from a succession of movements downdip from an eroding outcrop, if the results of erosion of the present outcrop are typical.

The extrinsic elements do not occur in the ore in large enough quantities to preclude their concentration from the host rock, and the metallic ions are capable of being precipitated by organic matter. In many places, however, molybdenum in these deposits shows little evidence of being deposited by organics.

## SYNGENETIC THEORY

The concept of dispersed uranium in the host rock with subsequent concentration has been considered above. Placer accumulations of uranium-bearing minerals, because of the observed solution effects in the ore deposits, appear to warrant consideration only as a source for the uranium emplaced in the present ore bodies by epigenetic solutions.

## RADIOGENIC LEAD

The general occurrence in this area of amounts of radiogenic lead greater than would be expected from the quantities of uranium now present does not point to one source of ore solutions above any other. The work of Brown (1962) on lead ores can be interpreted as implying a general separation of radiogenic leads from the parent uranium and thorium at some Precambrian time when the ratio of thorium leads to uranium leads was about 1.13. Differing lead ratios in small deposits and in the Mississippi Valley lead ores compared to the nearly uniform 1.13 ratio in most other large deposits indicates considerable imperfections in the separation. The widespread evidence of this imperfect separation would encourage us to expect anomalous amounts of radiogenic lead in uranium ore sources. Since both lead and uranium travel long distances in solution, we might expect that a specific set of circumstances would be required to assure that the lead-uranium separation at the time of deposition would be sufficiently clean to give the uranium a completely fresh start at disintegration. These specific circumstances appear not to have occurred generally at Grants. The situation is further complicated by the partial differential leaching of uranium and some of its daughters, notably radon, during redistribution of the Grants deposits (Granger et al., 1961).

## QUANTITY OF URANIUM AVAILABLE

Calculations of the amount of uranium available for forming deposits have been made by Gruner for Wyoming and Zitting et al. for Ambrosia Lake. These calculations tend to show that excess uranium is available. To make such calculations for the Grants region, certain assumptions are involved. For a granite leach theory, it is necessary to assume (a) distance to the Mogollon highland, (b) thickness of the Westwater Canyon over this distance, (c) grade of syngenetic uranium dispersed in the Westwater Canyon, (d) amount of loss of uranium into the Bluff and into sandy parts of the Recapture, and (e) amount of uranium lost downdip in bypassing the precipitants.

For an ash-leach theory, it is necessary to assume (a) thickness of Brushy Basin shales in the eroded area, (b) grade of uranium in shale, (c) proportion of uranium leached from shale, (d) proportion of leached uranium lost to the surface water, and (c) amount of uranium lost downdip in bypassing the precipitants.

For a hydrothermal theory, it is necessary to assume (a) amount of magma mobilized, (b) fluid content of magma, (c) concentration of uranium in fluid, (d) amount of mixing with surface water, (c) proportion of mixed solution entering host rocks and that entering other more permeable aquifers, and (f) amount of uranium lost downdip in bypassing the precipitants.

For all theories, the last item is critical because the most permeable aquifers, both fractures and sediments, have had the precipitants leached from them. Yet, because moving water follows the path of least resistance, most water would follow the most permeable path instead of zones containing protected precipitants. In addition, we must make an assumption as to whether we multiply the current ore reserves in the district by one or 100 to determine the amount of uranium that must be furnished by any proposed mechanism.

## THEORIES DEPENDING ON LESSER QUANTITIES

The considerations above show that the calculated amount of uranium available by any mechanism may vary by a factor of several million. The minimum assumptions result in marginal amounts of uranium in each instance, while the maxima are overwhelming.

If we accept the huge volumes of solution that are necessary to take care of bypassing the precipitants, it is tempting to propose a composite source in which uranium-bearing hydrothermal fluids mobilize ground waters in a formation containing anomalous amounts of dispersed uranium. This would explain some of the contradictory evidence which points to different sources.

If we do not accept the concept of huge volumes of ore solutions, it is necessary to narrow the range of controlling factors or to recirculate the solutions. The time between the emplacement of precipitant and the arrival of ore solutions may be narrowed to lessen the leaching of precipitant from the more permeable zones. If the precipitant is emplaced diagenetically, this means an early, perhaps pre-Cretaceous, entry of ore solutions. If the precipitant emplacement is connected with the uplift of the Zuni Mountains by downdip leaching and precipitation by lowering pH, then entry of uranium should follow shortly, perhaps by hydrothermal solutions, perhaps by leaching a different part of the sediments. If the organics and the uranium traveled together to the site of deposition *(Clark and Havenstrite,* this memoir), lack of organics in the most permeable pathways would not hinder formation of ore bodies if the acidic precipitating environment could be produced at the proper place.

It is possible to attack the problem through the timing of structural activity. If the precipitants were preserved from intrasediment leaching by being in sands of medium permeability throughout the period of Cretaceous burial, then, with the advent of Zuni uplift and fracturing, solutions might preferentially flow, either vertically or laterally along the fractured zones, redistributing the humates and bringing in uranium ions. The uranium might be either from hydrothermal sources or from the beds in the fractured zones, or both. A variation in this mechanism would picture ground water bringing the humates downdip to meet hydrothermal solutions rising along tension fractures.

A recirculation of ground water mobilized by hydrothermal activity was proposed by Waters and Granger. This theory has the advantage of conserving the uranium solutions by passing them several times through the sediments containing the precipitants.

## SOLUTION TRANSPORT

The paths taken by hydrothermal solutions are often considered to indicate their source. At Grants, the paths close to the deposits are in fractured, permeable sediments sandwiched between impermeable shales and suggest no immediate source. Elongation of stack ore bodies both vertically and horizontally along fracture zones indicates increased permeability along fractures. Easterly elongation of trend ore bodies suggests greater transmissibility in this direction, although it may result from the fluid mechanics of basin circulation rather than from variations in the rock itself. The lateral elongation of Ambrosia Lake and Poison Can on trend . di-cates that the fimil few miles of solution transport occurred **laterally through the host strata.** **us,** groud -water flow within the strata was determined by intrinsic sandstone permeability, by basin circulation, and by fracture zones.

Transport of hydrothermal solutions to the point of junction with ground water is a different problem. Maintenance of vertical passageways through silts, clays, and friable sandstones would appear more feasible when the rocks are undergoing tension rather than compression. Large faults separate the Zuni core from the surrounding sediments, but little alteration of limestone outcrops along these faults has been reported.

The complex relationships displayed by the deposits in the Grants region make it necessary to consider all possible pathways, both sedimentary and structural, as there is evidence that both were used by the ore solutions.

## LITHOLOGY

The largest deposits at both Ambrosia Lake and in the Laguna area occur in the thickest part of the favorable sandstone *(Clary, Mobley, Moulton,* this memoir). Within the lenses, the deposits occur in or near the central parts and may be elongated parallel to the long axis of the lenses. This is probably the result of increase in total flow where the sandstones were channelways for ground water redistributing the carbonaceous material and introducing the uranium or both.

The occurrence of large ore bodies in zones of medium permeability emphasizes the principle that the best hosts are those with enough permeability to permit entry of ore-bearing solutions in copious quantities, and yet without enough permeability to permit flushing of ore, organics, or zones of low pH.

## STRUCTURE

The uplift of the old Mogollon highland and the subsequent truncation of the Jurassic and Triassic rocks prior to the deposition of the Dakota Sandstone would allow solutions access into the unsaturated portions of such aquifers as the Entrada, Bluff, Westwater Canyon, and Jackpile sandstones. The uplift to the south coupled with gravity would have produced a hydrodynamic gradient by which solutions would move downdip in the truncated rocks toward the San Juan Basin. The fact that all the large deposits occur below the Dakota Sandstone has been used by some (Young, 1961) to postulate that the uranium was brought in following the deposition of the Brushy Basin sediments and before the deposition of the Dakota.

Solutions permeating the sediments could reach the Todilto Limestone through the underlying Entrada Sandstone at any time, but the overlying muds and silts of the Summerville Formation present a barrier except when opened by tension fracturing. Many Todilto ore bodies are limited to the upper part of the limestone—the situation we would expect if the deposits were derived from those in the Morrison. Todilto deposits from solutions permeating the Entrada should mineralize the base of the limestone more extensively.

All major Ambrosia Lake ore deposits occur within a broad, complex horst bounded by the northeast-trending Ambrosia Lake and San Rafael fault systems. The bounding faults and the San Mateo fault between them appear to connect with fault systems in the Zuni Mountain core. The San Rafael fault system is part of the western boundary of the Mount Taylor volcanic field. Travertine deposits and cinder cones are located near the fault traces (Thaden and Santos, 1957). The Precambrian rocks under the horst are shown by oil tests to be elevated about the surrounding basement complex. The Bluewater fault system in the Smith Lake area may extend to the Zuni Mountain core.

In the Grants uranium district as in metal mining districts (Bateman, 1948, p. 347) and in other uranium districts (Kushnarev et al., 1958), primary deposits do not occur in the most intensely fractured systems but are associated with subsidiary fracture systems. For example, Ambrosia Lake ore trends terminate against the strong northeast-trending Ambrosia Lake fault system; smaller parallel and diverging fractures control many ore bodies.

Multiple ore horizons are commonly related to fracturing. An example in a major Westwater Canyon deposit is Dysart No. 1, sec. 11, T. 14 N., R. to W. In the Churchrock area, Dakota, Brushy Basin, and Westwater Canyon deposits occur in or adjacent to the same fracture zone. Many ore bodies, including some of the largest and richest at Ambrosia Lake, are elongated both vertically and horizontally along fractures *(Clary, Mobley, and Moulton,* this memoir; Granger et al.). Near the outcrop in the Ambrosia Lake area, Todilto Limestone ore is present obliquely below Poison Canyon deposits along a common fracture system. Few drill holes extend to the Todilto Limestone through the Ambrosia Lake—Westwater Canyon deposits, and therefore no mineable deposits are known to occur directly below the major sandstone deposits, but several Todilto intercepts with grades as high as 0.22 percent $U_3O_8$ have been reported.

The pipelike structures visible in outcrop in the Laguna district appear to be good aquifers but most are unmineralized. Uranium ore is found in the Woodrow pipe and in a small pipe feature within the Jackpile ore body. Other circular structures containing ore are being discovered in the Ambrosia Lake area as mining progresses *(Rapaport* and *Clark and Havenstrite,* this memoir).

Todilto anticlines (Gableman, 1956; *McLaughlin,* this memoir) broken by axial and cross faults control most of the ore in the Todilto. For example, the sec. 18, T. 13 N., R. 10 W., ore body was mined to a hanging-wall axial fault. All major Todilto ore bodies are in fracture zones adjacent to the Ambrosia, San Mateo, and San Rafael fault systems; ore body clusters extend only two and one-half miles from these faults.

## IGNEOUS EFFECTS

Except along fractures, the unaltered trachyte, latite, and andesite series, basalt flows and basalt dikes of the Mount Taylor volcanic field are not highly permeable. The breccia and minor fractures surrounding the volcanic plugs could be conduits through which fluids migrate vertically or from bed to bed. Lack of radioactivity in the dikes coupled with only minor alteration in the wall rock surrounding these intrusives suggests that only a minimum quantity of solutions, with or without uranium, passed through these conduits.

The structure beneath the volcano is not positively known.

It was probably an eroded normal sag in which additional sagging and rejuvenation of the San Rafael fault developed as a result of the extrusion of the Mount Taylor complex. Solution pathways were changing during the period of adjustment, and circulation renewed or increased through the existing aquifers and through newly opened fractures.

## PRECIPITATION

The question of precipitation is critical. Regardless of their source, the ore-bearing solutions were dilute and stable during most of their travel through the sediments. As Gruner pointed out, a decided reaction is necessary to fix the uranium in the sediments.

Channeling of ore solutions through the limited volume of the more permeable aquifers reduces the dispersion of the uranium, but even so, concentrated supplies of a good precipitant are necessary to form a mineable deposit. If these concentrations of precipitants are poddy, discontinuous, varying in geometry, and scattered vertically and horizontally in the host rocks, then the ore deposits will have the same configuration, regardless of how thoroughly the ore solutions permeate the sediments.

If one bed has a good concentration of precipitants (Westwater Canyon) and another has none (Bluff), then the one bed will have ore bodies and the other will have none. If the paleoclimate of the Plateau favored the production of material leading to good precipitants (peat bogs, for example), then ore deposits are likely to be found in many places where beds laid down in such a climate have been protected. If the climate was such that only eolian sands were laid down, then the strata representing that time interval may well be barren. If the uranium in solution does not find a precipitant, then it is lost when the area is uplifted, eroded, or drained. Such a process is extremely wasteful unless a method for recirculating the ore solutions is found.

The multiple migration-accretion process proposed by Gruner is much more efficient, but this efficiency depends on a continuous supply of precipitant downdip. Grutt (1957, and personal communication) states that there is some fossil wood, kerogen, and petroleum in the Wind River Formation in the Gas Hills district in Wyoming, and that hydrogen sulfide derived from underlying petroleum pools is abundant in the waters of the district. Thus, when uranium is oxidized and mobilized, a supply of reductant is available to precipitate it not far downdip.

The most promising of the proposed natural precipitants were tested by Moore (1954), who measured their precipitating capacity in sulfuric acid at a pH of 2.45. Of the reagents tested, peat, lignite, and subbituminous coal extracted more than 98 percent of the uranium present. Bentonite clays extracted 28 percent, wood 4o percent, anthracite coal 34 percent, canneloid coal 8o percent, oil shale 21 percent, and gilsonite Io percent. Kelley and Kerr (1958) also precipitated uranium with oil at a temperature of 25o° C.

Bentonitic clays are only fair adsorbents of uranium in quantity, and the availability of surface for adsorbing is limited to the outer shell of a clay body. Organic materials are not restricted in this way. Although barren pieces of lignitic trash or patches of structureless organic material occur in many places, other pieces or patches of very large size may be thoroughly impregnated with uranium.

The structureless organic material has been called asphaltite, kerogen, asphalt, thucholite, vitrain, humic acid, humate, and dead oil. Breger and Deul (1959), Kelley and Kerr, Vine, Swanson, and Bell (1958), and others have attempted to classify the uraniferous "asphaltite" as coal or oil. Differential thermograms, infrared absorption spectrograms, and chemical analyses of "asphaltite" show similarities to both types but appear to be more similar to lignite than to oil. Kermac laboratory determinations (Zitting et al.) show humic acid as a main constituent of the "asphaltite" at Grants. Its obvious former mobility is the main reason for relating "asphaltite" to oil.

Assuming that the structureless organic material is related to coal and consists in large part of humic acids, humates, and other derivatives of cellulose and lignin, it may be emplaced in various ways. These materials are produced during the peat stage and travel in water as sols or solutions. They develop into a colloidal gel which is quite plastic and may be squeezed into fractures only a few microns wide. Emplacement from solution requires an environment of lowered pH or increased content of divalent positive ions such as $Ca^{++}$ (Vine, 1962). Gruner's multiple migration-accretion process might work at Grants if a receding acidic or calcic interface moved downdip during the pre-Dakota erosion. Lack of influence of the Ambrosia Lake dome on the distribution of uranium deposits would appear to preclude deposition by this process during the present erosion cycle.

Weight ratios of uranium to organic matter are not yet known at Grants. Ratios of :10 can be attained in the laboratory at room temperature using lignitic materials, and ratios of 1:100 at high temperatures by using oil. Vine suggested that after adsorption as $UO_2^{++}$, reduction by $H_2S$ yields $U^{4+}$ uranium minerals, leaving the lignite free to absorb more $UO_2^{++}$. This process might produce ratios much greater than 1:10.

The colloidal structure is probably essential for effective precipitation of uranium by solid lignite. Data from several sources (Francis, 1954) show a high colloidal surface in peat, lignite, and subbituminous coal, and the data of Moore show high uranium precipitation for the same materials. The irreversibility by pure water of the coal-uranium precipitation indicates chemical reaction rather than surface adsorption (Moore), but the permeability of the coal colloid increases the speed and effectiveness of the reaction in contrast to the impermeability of bentonite. Reversibility by pure water of the precipitation of uranium by charcoal (Moore) indicates that it is not a good material for fixing uranium in sediments subject to continued flow of ground water. This is borne out by the presence of much barren woody material in the sediments; for example, in the Marquez mine *(Weege,* this memoir).

The Cretaceous beds, the major coal- and oil-producing strata in the Grants region bear little uranium. The major uranium producing strata, the Morrison and Todilto, have produced little coal or oil. This reflects the ineffectiveness of oil as a precipitant and the flushing of humates from the coals.

## LITHOLOGY

Organic material in the Todilto Limestone cannot be disregarded, although visible fossils are uncommon. Anderson and Kirkland (1960) have described Todilto laminae composed of sapropel, which gives rise to the fetid odor emitted from a freshly broken surface of the limestone.

Organic detritus (logs, twigs, leaves, spore cases) is not only commonly disseminated in the Brushy Basin sands and upper Westwater Canyon, but there are detrital accumulations of the same order of magnitude as the smaller ore shoots. A few of these accumulations are mineralized but more are not. In contrast, the lower Westwater Canyon contains only minor quantities of either scattered or accumulated detrital organics.

Structureless organic films, probably humates, occur on grains or as interstitial fillings in both Brushy Basin and Westwater Canyon sands. Humates may occur as large concentrations comparable in size to ore bodies or disseminated almost imperceptibly through the sands. The large concentrations are conformable as a whole and disconformable in detail, but this is a rule with many exceptions. At a few locations, large concentrations of humates in the Brushy Basin and upper Westwater Canyon occur both with mineralized organic detritus and below unmineralized detritus. In the lower Westwater Canyon, humates may occur at some distance below detrital organics in the overlying sands or there may be no observable relation to such detritals. Over-all, the ratio of cellular to noncellular organic material in the Morrison appears to be of the same order of magnitude as that of some lignite deposits, particularly some of the noncommercial ones. In Kermac's Section 3o mine *(Clary, Mobley, and Moulton,* this memoir), a direct relationship between carbonaceous log accumulation and adjacent large quantities of structureless carbonaceous material can be observed.

Two other possible sources of the noncellular material were also noted by Granger et al.: (a) Humic acids were leached from lignite beds in the lower Dakota Sandstone which was deposited across the truncated Jurassic rocks, lowering the pH at an interface with stagnant waters, or waters high in divalent positive ions could flocculate the humic solution. (b) The streams depositing the Morrison contained a dissolved complement of humic matter derived from vegetation decaying near the headwaters of the streams. This theory would explain the elongation of the carbonaceous material parallel to the sedimentary trends of the Westwater Canyon, but large loads of soluble humates are more common where streams are meandering through a heavy soil cover than where they are eroding a highland.

The humates have been emplaced both along the depositional trends and along faults and joints. Fluctuations in the fresh-water interface as well as in the water table may have tended to redistribute the material. The intimate association between ore and the humates and the fact that very little trend ore has been found there without humates indicate that it was the major precipitant of the uranium. From this it might be inferred (1) that the humates and the uranium-bearing solutions were closely associated in time and space when emplaced at the present site or (2) that the humates are almost the only precipitant for the uranium in solutions which completely permeated the sediments.

### STRUCTURE

The presence of petroliferous beds and geological structures compatible with occurrences of oil and gas are important features within the Grants region. If natural gas rich in a reducing agent such as hydrogen sulfide escaped from subterranean reservoirs via faults and fractures connected to the sites of present deposits, reducing environments similar tc those described in Wyoming (Grutt) may have formed.

Calcium carbonate is an effective agent to remove uranium from acid solution. Massive limestone replacement in fractured anticlines of the Todilto Limestone suggests such a combined structural and chemical control.

Faults and folds on basin flanks would influence the position of the pressure or pH fronts postulated by Noble.

### SOLUTION EFFECTS

The high-angle surfaces of "roll" ore bodies do not conform to the usual concept of an oil-water interface. The difference in specific gravity of oil and water, combined with slow fluid movement through a sandstone of medium permeability, should have permitted the formation of nearly level interfaces if oil were present. Redistribution of ore after stabilization of asphaltic residues requires very active reagents. The stability of uraniferous organics has been noted by many workers and may be a product of radiation (Hausen, 1959).

Precipitation of uranium in the Todilto by organic agents requires a separate age of uraninite-fluorite replacement. Little evidence of organic matter has been observed in the fluorite ores, which are a minor part of the Todilto total. A later age of fluoritization, perhaps at the same time as redistribution of the Westwater Canyon ores, would appear to be a reasonable assumption.

## ENRICHMENT OF ORE

The stack ore bodies may represent a considerable later enrichment of the ore in the Morrison at Ambrosia Lake, but whether or not the whole enrichment is due to oxidation is debatable. Although the stack ore has a lighter color and less organic carbon and molybdenum, in many places it is impossible to pick a contact between the two because the visual changes are very gradual. In other places, trend and stack ore are separate. Trend ore is displaced by faults and stack ore follows faults, suggesting that stack ore is younger. However, the fault relationships may apply only to the bodies of precipitant, and all ore may be younger than the faulting. It is possible to postulate a reversal of the stack and trend ore ages. This process would consist of original deposition in the fracture zones, later leaching of uranium, lead, and molybdenum, and final reprecipitation of the leached metals along the trend.

### SOLUTION EFFECTS

Oxidation of Todilto ores has resulted in leaching some of the uranium that was near the outcrop and dispersing the oxidized ore from the fold structures into bedding and joint planes of the platy part of the limestone. Oxidation and redeposition of the sandstone ore in the Poison Canyon trend during the present erosion cycle *(Rapaport,* this memoir) results in mineable ore when an impermeable layer directly underlies the older mineral deposit, but enrichment is not obvious.

There is little direct evidence of what happens today when the uranium arrives downdip at one of the ore bodies below the water table. No precipitant is known, as present evidence indicates that the organic material in the ore bodies has been used up, and no evidence of hydrogen sulfide now in the Westwater Canyon ore is known. There are small veinlets of black uranium and vanadium minerals and radiobarite cutting the ore zones. Mill-head samples representing several hundred to several thousand tons from separate ore bodies are in radioactive equilibrium. The experience of the Grants Branch A.E.C. Office with more than one thousand individual grab samples is the same as that recorded by Granger et al. (their fig. 7); ore-grade samples are slightly deficient in daughter products, and low-grade samples are relatively enriched in daughter products. The picture is the same in both trend and stack ores. The process envisioned is the minor migration of ore into the low-grade zones combined with a greater migration of some of the more soluble daughter products such as radon. The limited movement of both uranium and its daughters is shown by the over-all equilibrium in the mill pulps, but our evidence is limited by the half-lives of daughter products to the last 300,00o years.

The radiochemical suites of Granger et al. (their fig. 8) suggest recent movement of short-lived daughters, but any uranium loss could have taken place over the entire life of the deposit or during the derivation of stack ore from trend ore that Granger postulates.

In times preceding the present erosion cycle, the enrichment picture must have been different. Massive stack ore bodies and recrystallized, fluoritized limestone ore bodies were deposited. It is not clear whether the stack ore was derived from the trend ore or whether low-grade material was leached from updip deposits and redeposited at the present site. The carbon deficiency in some of the stacks appears to necessitate another type of precipitant. It may have been hydrogen sulfide, although there is no direct evidence of its source. Stack and trend ore are so closely associated, however, that hydrogen sulfide produced by anaerobic bacteria feeding on the trend organics is a plausible assumption.

### STRUCTURE AND IGNEOUS EFFECTS

Much stack ore is controlled by northeast-striking faults and by north-striking fractures, some of which are en echelon in northeast-trending zones. The bounding faults of the Ambrosia Lake horst and the Mount Taylor volcanic field also trend northeast. Whether or not volcanic solutions added uranium to the deposit, it is noteworthy that deepening of the McCartys sag during the Miocene-to-Pliocene eruptions from Mount Taylor probably put the nearby northeast fractures in tension and may have triggered the sag along the San Mateo fault. If the fault data are correctly interpreted as meaning a young age for the stack ore, its emplacement may have taken place during this period of tension fracturing when volcanic energy was available for circulating solutions and for furnishing fluorine for fluoritization of part of the Todilto ores. On the other hand, if the primary ore was emplaced along the faults, then the Miocene age for ore compatible with Perry's suggestion regarding the Woodrow pipe might become more attractive.

In general, hypabyssal igneous activity on the Colorado Plateau, including Mount Taylor and the Utah, Colorado, and Arizona laccoliths, has been considered to be postore. There is direct evidence for this in the Carrizo intrusion in northeastern Arizona. Even so, it would seem unusual for such a quantity of igneous activity to take place in the midst of great ore districts without affecting them in some way. Redistribution of originally sedimentary deposits by volcanic waters is another way of reconciling much contradictory evidence.

Emplacement of ore along middle to late Tertiary faults is largely limited to the west side of Mount Taylor where the major faulting took place. Except in two pipes, little enrichment along fractures has been reported at the Jackpile mine on the east side of the volcano, and the nearby Paguate deposit has not yet been fully evaluated *(Wylie,* this memoir).

## PROTECTION OF THE DEPOSITS

Many ore bodies on the Colorado Plateau have been lost by weathering and erosion. At Grants, this loss appears to be confined to the Todilto, to the Poison Canyon trend, and to the Churchrock area.

Outcrops of mineralized Todilto occur south of U.S. Highway 66 near Laguna. This may be interpreted as indicating a mineralized belt of Todilto 12 miles wide. The trend of Poison Canyon ore bodies *(Rapaport,* this memoir) extends from sec. 29, T. 13 N., R. 8 W., to sec. 19, T. 13 N., R. 9 W. Westward beyond this point the trend is lost by erosion. Much Poison Canyon ore has probably been moved downdip by leaching. The Westwater Canyon ores at Ambrosia Lake have suffered little from leaching and none from erosion.

In considering protection against excess leaching of ore deposits at Ambrosia Lake, two general types of protection are needed: first, protection of the precipitant until the introduction of uranium and, second, protection of the precipitated uranium until mining.

### PROTECTION OF THE PRECIPITANT

The Triassic and Jurassic period were characterized by a sequence of continental rocks both eolian and fluvial, but the Cretaceous was marked by marine transgressions and regressions with the associated continental sedimentation behind the migrating shore line. This change in environment may be significant in the distribution of the precipitant and subsequent uranium deposits.

Since the Cretaceous contains abundant carbonaceous material and sandstones which arc good aquifers there has always been some speculation as to why this sequence in the Grants uranium district is nearly barren above the Dakota, especially since the Toreva Sandstone (Gallup equivalent) contains some uranium deposits in the Black Mesa basin of northeastern Arizona (Clinton, 1956). If uranium were present in streams depositing the continenal Cretaceous beds, it might have been either precipitated in the coastal humate-rich lagoons or lost into the Mancos sea. Vine suggested that soluble uranyl humates would pass on through the coastal swamps and enter the sea. The Diamond No. 2 mine (sec. 33, T. 15 N., R. 17 W.), one of the largest known ore bodies in the Dakota, is confined to a zone of interlensing deltaic and lagoonal sediments, but such ore bodies are rare in the Cretaceous. If humates were deposited in the permeable beach sands, they have now been flushed downdip into the San Juan Basin. Evidence of continued flushing is the presence of fresh water at the Hospah oil field, about 20 miles north of Ambrosia Lake, below the oil in the Gallup Sandstone and also below that in the Dakota sandstone (King and Wengerd, 1957). The Westwater Canyon, being less permeable, would tend to restrict ground-water movement and less flushing would occur.

### PROTECTION OF THE ORE

Water-table protection seems to afford the most effective protection for the ore. Although a pressure gradient from the rim of the San Juan Basin inward does exist, little leaching of the ore or of the precipitants is apparent below the water table. Rising water tables would protect ore bodies from leaching and lowering water tables would expose deposits to leaching. The Ambrosia Lake dome tends to elevate the western part of the Ambrosia Lake area above the general water table; consequently, oxidation is encroaching on the western ore deposits. Howeyer, calcite impregnation in some pods of ore around the dome preserved the ore even at considerable distance above the water table. Todilto ore is near the surface, above the water table, yet recrystallized calcite preserves the ore deposits from oxidation until exposed by erosion.

If clay gouge is present along a fault trace, it may serve both to hold mobile organic material and to shield the area from leaching. The excess of organics coupled with the shielding of the clay tends to preserve uranium deposits stacked along its boundaries from solutions moving laterally in the sands, but not from solutions moving along the fault.

## SUMMARY AND CONCLUSIONS

In this summary, the ore processes will be treated in order of the decreasing availability of data, which is nearly the reverse of their chronological order.

### PROTECTION

Perhaps 75 percent of the original ore in the Todilto has been lost by erosion if we assume that the limestone held ore deposits as far south as indicated by the deposits south of Laguna. Much Poison Canyon ore has also been eroded. Erosion has not yet reached the Westwater Canyon ores at Ambrosia Lake and has made only a minor reduction in the ores in the Jackpile sand near Laguna.

Ground-water leaching of the Ambrosia Lake deposits during the present erosion cycle has occurred, mainly along large fault systems, and the equilibrium data indicate little over-all loss to the main deposits lying mainly along subsidiary faults. Leaching of deposits in the Poison Canyon trend has left ghost ore bodies in some instances and highly oxidized ores in others.

Leaching of humic precipitants from the Cretaceous sands is probably the cause of their lack of large ore bodies. The repeated transgressions and regressions of the Cretaceous seas must have circulated large amounts of water through these permeable beds, removing or dispersing the soluble constituents.

### ENRICHMENT

Deposition downdip from the leached ore in the Poison Canyon trend has produced oxidized ore bodies, and oxidized ore spreads around uraninite ore bodies in the Todilto, filling joints and bedding plane fractures. There is little evidence to indicate that these oxidized deposits are richer than their parents, and many of them are leaner.

Emplacement of ore along northeast- and north-trending fracture systems was a different type of process. Relationship to fossil water tables is not in evidence. The ore is largely related to organic content, but some carbon-deficient stacks are known. Fault displacements in trend ore may indicate a younger age for the stack ore, which in this instance could be considered an enrichment of the trend ore. The source of uranium in the enriching solutions might have been the trend ore, but the presence of molybdenum halos around trend ore and their absence around stack ore does not seem to be a likely result of trend-ore leaching. The uranium in the stacks could have been brought in by solutions percolating downdip through the Westwater Canyon or from hydrothermal solutions entering the Westwater Canyon through fractures.

It is also possible that the stack ores were emplaced first and that following solutions, either slightly or much later, leached uranium, lead, and molybdenum from the stacks and deposited them in the east-to-southeast configurations that are called *trend ores.* The evidence against this process is that stack ores follow faults and trend ores are displaced by faults; but this may only reflect the relation of the precipitant bodies to faults and the coincidence of later uranium with the precipitant distribution. In any event, the differing elemental composition of stack and trend ores suggests deposition from differing types of solution and probably differing times of deposition.

The fluoritization of the Todilto ores may have taken place at the same time as the enrichment of the sandstone ores. Fluoritization accompanied intense recrystallization of the limestone in northeast- to north-trending zones of intensified fracturing parallel to those controlling the stack ores in sandstone. Like the stack mineralization, the fluoritic ores represent a mineralizing intensity not observed in progress today.

### SOLUTION TRANS PORT

Effects such as "roll" ore bodies indicate deposition of uranium from solution, and the wide lateral spread of sandstone deposits in the Morrison suggests that ground water was the main constituent of the ore-bearing solutions.

Several nearly barren strata both above and below the Morrison and Todilto are much more permeable than the ore hosts, and much greater quantaties of all types of circulating waters must have passed through the Bluff and Dakota, for example, than through the Westwater Canyon. The permeable and semipermeable strata are sandwiched between nearly impermeable silts and clays, which are also nearly barren. The limitation of ore to the semipermeable beds suggests that a good ore host should be permeable enough to permit the passage of large quantities of ore-bearing solutions but impermeable enough to prevent excess leaching of parcipitants prior to ore deposition or leaching of ore after deposition. Occurrence of ore along fracture zones and in the thickest parts of the Morrison sands suggests that the Morrison as a whole has less than optimum permeability and that fracturing or special sedimentary facies are required to bring it into the optimum range. In some instances, more intense fracturing raised the permeability well above the optimum range.

Regional permeability in the sand-clay sandwich has been brought further into the third dimension by major fracture sets which penetrate the entire sedimentary blanket and in some instances penetrate the crystalline basement complex as well. In slightly indurated elastic sediments, fracture systems provide considerable vertical permeability when the rocks are in tension and the fractures open. Two northeast-trending fault systems isolate the Ambrosia Lake ores on a horst, displace the basement rocks, and probably extend southwest to the core of the Zuni Mountains. These major fault systems are barren, but lesser fractures of the same set are heavily mineralized. The Bluewater fault, a major north-trending fracture that passes near Smith Lake, is barren, but a lesser, related parallel fault a few miles to the west is the site of considerable ore in the Black Jack No. 1 mine. Ore bodies at Churchrock are elongated along north- and northeast-trending fracture zones. Fracture control is not clearly evident at the Jackpile, but Jackpile, Ambrosia Lake, Smith Lake, and Churchrock areas form so strong a lineation parallel to the northeast flank of the Zuni uplift that there is some justification for calling it a mineral belt.

These three sets of solution pathways may be related to times in the structural history of the region when tension might have kept them open; (1) the southeast lineation of the mineral belt might correspond to relaxation following the uplift of the Zuni Mountains, (2) the northeast lineation might correspond to gravity adjustments along the San Rafael and San Mateo faults during extrusion of the Mount Taylor volcanics, and (3) the north lineation may correspond to Tertiary adjustments related to the same cause as the Rio Grande trench. Ground-water circulation must have been rejuvenated during these three times, and volcanic energy was available for solution transport during two of them.

## PRECIPITATION

Lignitic material and its humic derivatives satisfy the requirements of mobility, occurrence in fluvial sediments, precipitating capacity, and stability after combination with uranium. Dispersed sources of humates are possible, but concentration of the dispersed matter is difficult. The limited, poddy distribution of ore-bearing humic masses suggests that they were derived from local lignitic concentrations not more than a few thousand yards distant. Although humates permeate large volumes of rock as interstitial films, the actual volume of humic material is not too great to be derived from inferred local sources, especially when we consider that cellular material commonly constitutes only ten percent of coal seams.

The location of the precipitants controls the location of the ore. Permeability, whether sedimentary or structural; geochemical conditions; and location of source material control the location of the precipitants. Plateau-wide climates produced the lignitic source material in Morrison time. Continental Morrison sediments of medium permeability provided the proper environment for the derivation and protection of humic matter in certain limited locations. Later, but pre-Mount Taylor, fracturing offset some lignitic bodies and changed the pattern of ground-water movements, allowing the emplacement of humate bodies transecting sedimentary features. A minor amount of humate distribution may have been done by the ore solutions themselves, but in time the organic-controlled ore bodies became stable. The over-all radiometric equilibrium indicates lack of major redistribution in the last 300,00o years.

## SOURCE OF SOLUTIONS

Two groups of factors contribute to the controversy over the source of the solutions which initially emplaced the Grants deposits. One group is concerned with the Plateau-wide extent of uranium deposits in the Morrison Formation; any source of solutions at Grants must also bear a reasonable relationship to the source of solutions for Plateau £deposits. The second group is concerned with the varied history undergone by the Morrison in the Grants area. The sands and shales were deposited on a fluvial fan or delta by distributary streams, resulting in a three-dimensional network of sand and silt lenses and clay seams in which only the roughest kind of stratigraphic correlation is possible. Successive waves of tectonic compression, relaxation, uplift, and sinking have left several distinct fracture sets impressed on the rocks. Two known periods of volcanism, one during deposition and one during the late Tertiary, have contributed ash, lava, and hydrothermal fluids to the area. Two periods of erosion and weathering, one pre-Dakota and the other Pliocene to Recent, have denuded the Morrison outcrops. Between these two periods of erosion, the Morrison was buried beneath several thousand feet of Cretaceous marine sediments. This history affects the location of mineable deposits because the precipitants have existed in the Morrison throughout all of it, and the precipitants control the location of the ore. The conflicting mass of superposed evidence has been variously interpreted.

Separating the evidence which bears on source of solutions is also difficult because the separation must be made, not only as to time and effect, but as to whether it affected the ore or only the precipitant. Ground-water effects of the type in progress today can probably be neglected because of its comparatively mild character and because of the over-all radiometric equilibrium which indicates little major movement of large, deep ore bodies during the last 300,00o years. Ash-leach effects can probably be neglected because of lack of major silicification of the Westwater Canyon and because of the demonstrated impermeability of bentonitic clays to heavy metal ions. Fault displacements have to be neglected because we cannot determine whether the faults offset preore organic masses or ore-bearing organic masses. The regional quartz-feldspar-anatase-kaolin alteration could be due to their ore-bearing solutions or to humic solutions related to the precipitants.

The remaining evidence is valuable mainly as a base for assumptions rather than for more concrete inferences:

(a) The mineral belt and the trend ore within it are elongated parallel to the Zuni uplift and to sedimentary trends.

(b) Stack ore may occur in multiple horizons and is elongated along northeast- and north-trending fault sets which are assumed to be earlier than or contemporaneous with the Mount Taylor volcanism.

(c) Major fault systems bound the Ambrosia Lake area, but they are barren and hematitic to depths of at least 1400 feet.

(d) Some pipe structures are mineralized but most are not.

(e) Bentonitic derivatives of volcanic ash are common in the Morrison, and we assume that there were hydrothermal contributions from the same volcanism, either through the pipes as suggested by Wylie (this memoir) or through pre-Dakota fault systems.

(f) The Westwater Canyon averages about 100 ppm uranium within the Grants district but outside the ore bodies.

(g) Trend ore, stack ore, and Todilto ore have slightly different mineralogic and elemental composition.

(h) The Morrison is ore-bearing in many districts throughout the Colorado Plateau.

(i) Igneous activity that is probably postore occurs in all the major districts of the Colorado Plateau.

These points of evidence are compatible with uranium deposits derived completely from source-bed leaching, but they are not definitive. The obviously sedimentary features of the deposits are inherent in the theory, and effects which are more easily attributed to hydrothermal activity are thought to be the result of later, barren volcanic emanations.

The evidence is also consistent with a hydrothermal source, but not definitive. The obviously sedimentary features of the deposits are thought to be related to the sedimentary source of the precipitant, and effects which are more easily attributed to hydrothermal activity are assigned to the ore-bearing solutions.

To be effective throughout the Plateau, source-bed theorists must assume that both the southerly source of the Westwater Canyon and the westerly source of the Salt Wash were rich in uranuim. Hydrothermal theorists must assume a multiplicity of uranium sources throughout the Plateau in Laramide or Tertiary time. Either these sources furnished vast volumes of solution to permeate many permeable beds or the solutions were recirculated by continued igneous activity. Perhaps the Plateau-wide scope of Morrison uranium should be attributed to hydrothermal activity and related to Morrison volcanism, which contributed uranium to the surface waters. This dispersed, syngenetic, hydrothermal uranium could then be moved to Jurassic sites of precipitation by volcanically activated ground waters, but sites in parts of the Cretaceous are more difficult to explain.

The authors remain divided as to which theory has the most merit. It is suggested that the best places to prospect for large deposits are those where both hydrothermal and source bed uranium are possible.

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# *Structure and Volcanism, Grants Ridge Area*

PAUL F. KERR AND J. THOMAS WILCOX

## ABSTRACT

Rocks of Precambrian to Cretaceous age on the northeastern edge of the Zuni uplift have been penetrated by volcanism marginal to Mount Taylor. Volcanic emplacement began with violent eruptions of rhyolitic tuff in the vicinity of East Grants Ridge. The perlite-obsidian-rhyolite complex was extruded through the tuff as a highly viscous melt which formed both a central dome and a peripheral perlite zone. Formation of the varied rock types in the complex was caused by differential distribution of volatiles and different cooling histories of various parts of the complex.

The felsic phase was followed by eruption of porphyritic basalt flows from central vents and by the formation of red scoria cones on top of the flows. Igneous activity was apparently concluded by the intrusion of basaltic breccia and lamprophyre dikes at the western end of East Grants Ridge.

The mafic phase of igneous activity was later than displacement along the San Rafael fault and was localized by the fault. The relation of the felsic igneous activity to the time of faulting is uncertain.

Apparently uranium deposits in the Todilto Limestone must have originated before the East Grants Ridge volcanism and after the deposition of the Todilto.

## INTRODUCTION

Grants Ridge, East Grants Ridge, and West Grants Ridge lie immediately north to northeast of Grants, New Mexico, and form a discontinuous ridge about nine miles long and one to two miles wide (fig. ). The east end of East Grants Ridge is a felsic volcanic complex while the remaining ridge tops are basalt-capped mesas.

Grants Ridge and East Grants Ridge constitute an area of complex volcanic activity near important uranium deposits and have been studied for several years.

## SEDIMENTARY ROCKS

### TRIASSIC ROCKS

*Chinle Formation*. The oldest sedimentary unit exposed in the Grants Ridge area is the Triassic Chinle Formation. It is about 85o feet thick and consists of a cherry-red mudstone with interbedded sandstone, siltstone, and beds of limestone conglomerate (Rapaport, Hadfield, and Olson, 1952). Numerous exposures of the formation occur on the flanks of Grants Ridge, particularly toward the west end.

### JURASSIC ROCKS

Overlying the Chinle is a series of Jurassic sediments between 800 and 1000 feet thick, in order older to younger, the Entrada Sandstone, the Todilto Limestone, the Summerville Formation, the Bluff Sandstone, and the Morrison Formation. Because of faulting and incomplete exposures in the Grants Ridge area, only estimates of thickness are possible.

*Entrada Sandstone.* This is a compact quartz sandstone, red-orange except for a transitional zone below the Todilto where the color is generally light gray or variegated. Cross-bedding is common and the Entrada in the Grants area is estimated to be 15o to 25o feet thick (Hilpert and Moench, 1960).

*Todilto Limestone.* In the Grants area, the rock is a nonmarine limestone between io and 20 feet thick. The formation generally comprises a lower "platy" zone, a middle "crinkly" zone, and an upper "massive" zone. The unit is locally recrystallized, notably at the F-33 mine of The Anaconda Company. Small-scale folding and thrust faulting are widespread. These features are usually intraformational but may extend a few feet into the underlying or overlying formations. A characteristic feature of the Todilto Limestone is the petroliferous odor exhibited by the freshly broken specimens.

*Summerville Formation.* The Summerville Formation consists of red to light gray sandstone, siltstone, and shale approximately zoo feet thick.

*Bluff Sandstone.* The Bluff is a massive, fine- to medium-grained quartz sandstone. It is gradational into the underlying Summerville Formation and is about zoo feet thick. The unit is prominently exposed on the northern side of East Grants Ridge, above the F-33 mine.

*Morrison Formation.* The Morrison Formation is poorly exposed on the Grants Ridges, although each of the three members in the Grants area may be recognized at the western end of East Grants Ridge. At Red Bluff, about five miles north, the Morrison has a total thickness of about 30o feet (Freeman and Hilpert, 1956). The section measured on East Grants Ridge is only about 200 feet thick, but part of this section may be omitted by faulting.

### CRETACEOUS ROCKS

*Dakota Sandstone.* The Morrison Formation is unconformably overlain by the Dakota Sandstone. The Dakota is a well-cemented, fine- to medium-grained quartz sandstone, locally conglomeratic. The formation is about 85 feet thick. A carbonaceous shale bed is frequently present at the base of the formation. The contact with the underlying Brushy Basin Member of the Morrison Formation is exposed in several outcrops on or near the Grants Ridges and provides a good stratigraphic marker.

*Mancos Shale and Mesaverde Group.* The Dakota Sandstone is overlain by about 70o feet of black Mancos Shale which is in turn overlain by sandstone, shale, and local coal lenses of the Mesaverde Group. The Mancos is poorly exposed between hogbacks of the more resistant sandstones

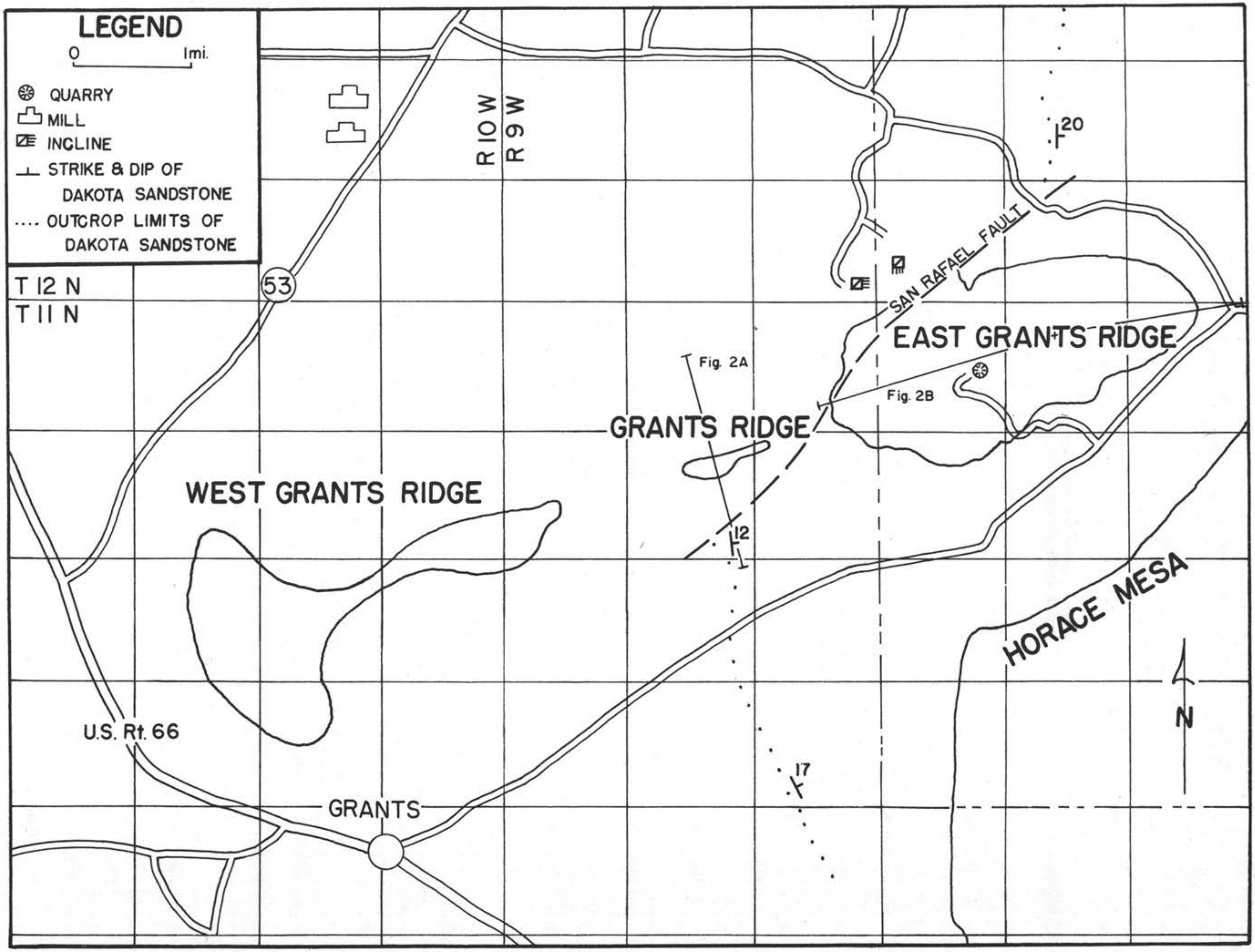


Figure 1

Geologic map of the Grants region, showing the Grants mineral belt, the limestone ore trend, and mining areas above and below. The Mesaverde Group is well exposed on the southern side of East Grants Ridge along both sides of the canyon and at the eastern end of the ridge below the perlite quarry. A prominent hogback north of East Grants Ridge also exposes Mesaverde sandstone.

## ALTERATION

### BLUFF SANDSTONE

A conspicuous feature of the Bluff Sandstone in the Grants Ridge area is its ochre-yellow color in outcrops in contrast to a characteristic red north and east of the Grants Ridges. The transition from red to yellow occurs within a few hundred feet horizontally and is clearly exposed near Red Bluff, about five miles north of the Grants Ridges. The sharp boundary suggests an alteration effect rather than an original feature. The nature of the alteration is still under study, but the marked color change may represent original hematite cement altered to limonite.

### SUMMERVILLE FORMATION

The normally red shale of the Summerville Formation is altered green in places over uranium ore bodies in the Todilto Limestone. Study by Megrue (1962, Columbia Univ., Ph.D. thesis) indicated that true montmorillonite of the original Summerville has been altered to mixed layer montmorillonite-illite and illite-chlorite. Megrue suggested that the alteration of true montmorillonite to illite is indicative of temperatures above one hundred degrees centigrade, as based on the work of Caillere and Henin (1949) and Weaver (1958).

## STRUCTURAL FEATURES

### SAN RAFAEL FAULT

A partly concealed but important structural feature of the Grants Ridge area is the San Rafael fault (figs. i, 2A). In the area studied, the fault trends northeast-southwest and extends from south of Grants Ridge to north of East Grants Ridge. It is exposed on the southern side of Grants Ridge, where the upper part of the Chinle is in contact with the upper part of the Brushy Basin Member of the Morrison Formation. This indicates a stratigraphic displacement about equal to the thickness of the Jurassic section, or 800 to 1000 feet, the south block being displaced downward with respect to the north block. The Dakota hogbacks on either side of the Grants Ridges are offset about three miles. This offset is probably caused by displacement along the San Rafael fault.

The trace of the fault through East Grants Ridge is concealed by younger basalt flows. At least one basaltic volcanic vent and possibly several have been localized along the fault.

### OTHER FAULTS

In addition to the San Rafael fault, a number of smaller more or less parallel faults occur near the western end of East Grants Ridge. In the F-33 mine, about 1100 feet from the portal, the Todilto Limestone is downthrown about loo feet on the southeastern side of a fault. Uranium ore is offset by this fault, which is probably a part of the San Rafael fault zone. Farther southwest, a number of minor normal faults offset the sedimentary strata. Along two of these faults, the displacements are about 20 feet.

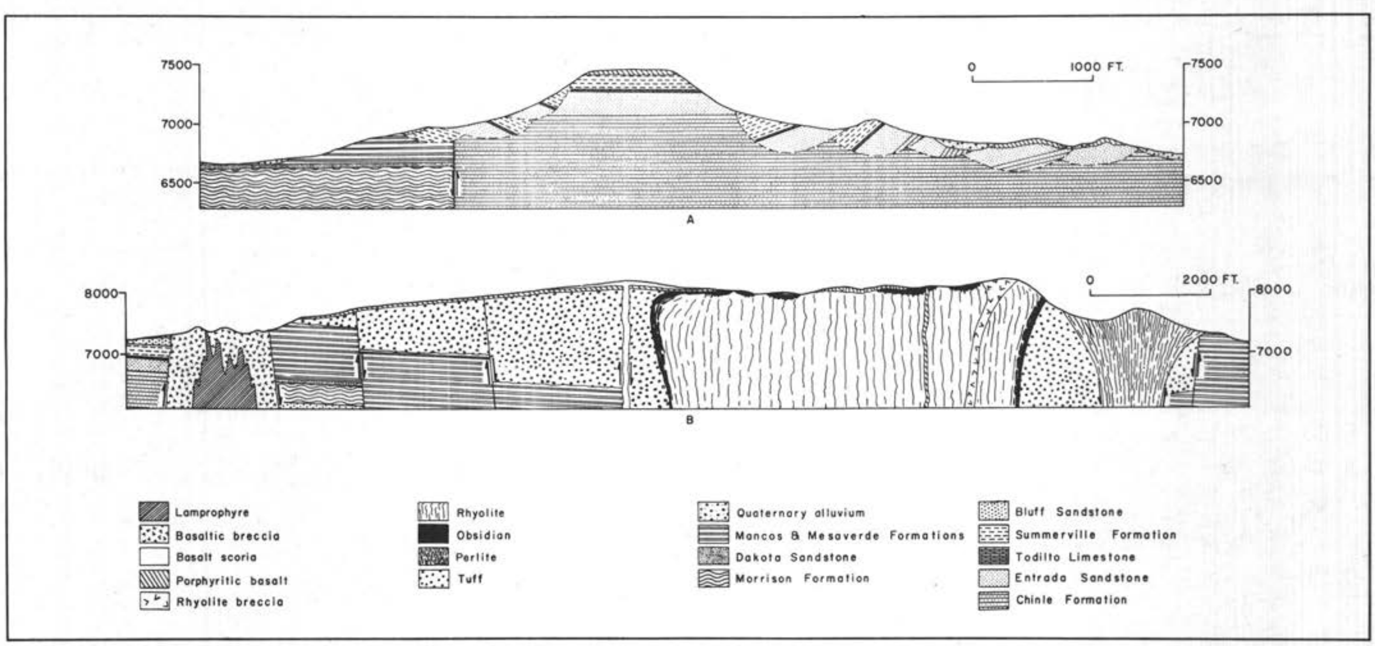


Figure 2

A. Cross section through Grants Ridge, showing slump blocks and San Rafael fault

B. Cross section through East Grants Ridge, showing relation between volcanic units

## LANDSLIDES

Numerous basalt-capped blocks form an arcuate pattern bordering Grants Ridge (fig. 5). The blocks measure as much as 2000 feet long and several hundred feet wide. Exposures of Entrada, Todilto, Summerville, and occasionally Chinle strata occur on these blocks. The beds generally dip inward toward the ridge at angles up to 7o degrees, suggesting rotation of the blocks (fig. 2A). The elevation of the Todilto Limestone in each successive block is lower with respect to the resistant central mesa, and outer blocks as a whole rest at lower elevations than inner blocks. The blocks are similar to several other occurrences on the Colorado Plateau which have been described as Toreva-blocks (Reiche, 1937) or slump blocks (Strahler, 194o). Such an interpretation seems warranted around Grants Ridge. The blocks are restricted to an area underlain by Chinle mudstone, and it is probable that failure occurred in this incompetent unit. On the southern side of Grants Ridge the slump block material has moved southward across the San Rafael fault, concealing the fault trace. Here Triassic and Jurassic strata form an apron which rests upon Cretaceous Mancos and Mesaverde strata on the downthrown side of the fault (fig. 2A).

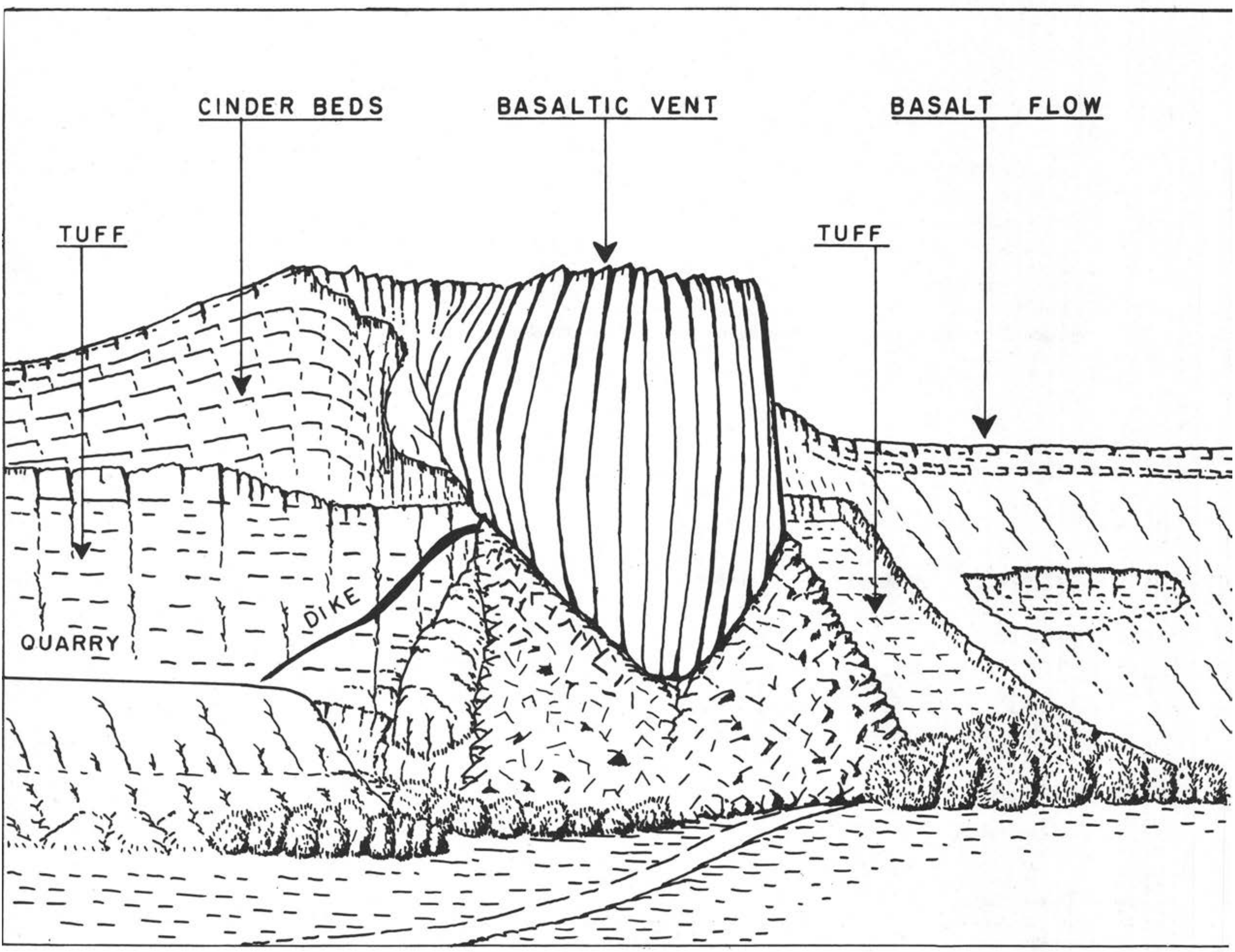


Figure 3

SKETCH OF BASALT PLUG AND PUMICE QUARRY. THE PLUG RISES VERTICALLY THROUGH TUFF. IT FED THE MORE OR LESS HORIZONTAL FLOWS OF THE HILL TOP

## VOLCANIC EMPLACEMENT

Volcanic rocks on the Grants Ridges fall into two distinct groups: an early felsic phase and a later mafic phase (fig. 2B).

### FELSIC PHASE

#### Tuff

The earliest volcanic activity was one or more violent eruptions of rhyolitic tuff. Eruptive violence is indicated by scattered granitic blocks from the Precambrian basement, some as large as five feet in diameter.

The tuff comprises fragments of pumice, rhyolite, and locally granitic fragments and boulders (Precambrian) in a matrix of fine-grained white ash. The unit forms a peripheral zone around the later glass-rhyolite complex and extends from near the western end of East Grants Ridge eastward to the vicinity of the perlite quarry. Bedding in the tuff is locally well developed and is essentially horizontal.

The presence of the granitic boulders in the tuff in the vicinity of East Grants Ridge and their apparent absence in the tuff exposed on La Jara Mesa to the north suggests that the tuff was erupted from a local vent rather than from a source on Mount Taylor.

#### Perlite-Obsidian-Rhyolite Complex

The perlite-obsidian-rhyolite complex forms the eastern part of East Grants Ridge. It occupies a roughly oval-shaped area about one mile wide and one and a half miles long and rises about 800 feet above the floors of the surrounding canyons. The complex consists of two parts: a central dome and a peripheral zone, the two being separated by rhyolitic tuff.

*Central dome.* The central part of the perlite-obsidian-rhyolite complex has been called a stock by a previous worker (Johnston, Univ. N. Mex., master's thesis); however, Thaden (1958) uses the term *cumulo-dome.* Since the body has a number of characteristics in common with volcanic domes described by Williams (1932), Kelley and Soske (1936), and others, the term *dome* appears more acceptable.

The dome consists of a rhyolite core surrounded by a collar of obsidian and perlite. In addition, much of the core is covered by a crust or capping of obsidian and perlite. At the eastern end of the dome, the rhyolite core has been intruded by rhyolite breccia.

Flow banding is locally prominent in both the rhyolite and the obsidian. The contact between these units is gradational, and the transition, where observed, is accompanied by no change in the attitude of the flow banding. This relationship suggests that the rhyolite and obsidian are contemporaneous. The same relationship exists between perlite and obsidian. The flow banding dips outward at the top of the cliffs which surround much of the dome but inward at the base of the cliffs, suggesting a bulb shape for the dome.

Canyons which dissect the top of the dome frequently cut downward through the perlite and obsidian into rhyolite. It is probable that the upper glasses constitute a crust which formed during extrusion of the dome. At the southwestern end of the dome, the glasses of the collar and the capping

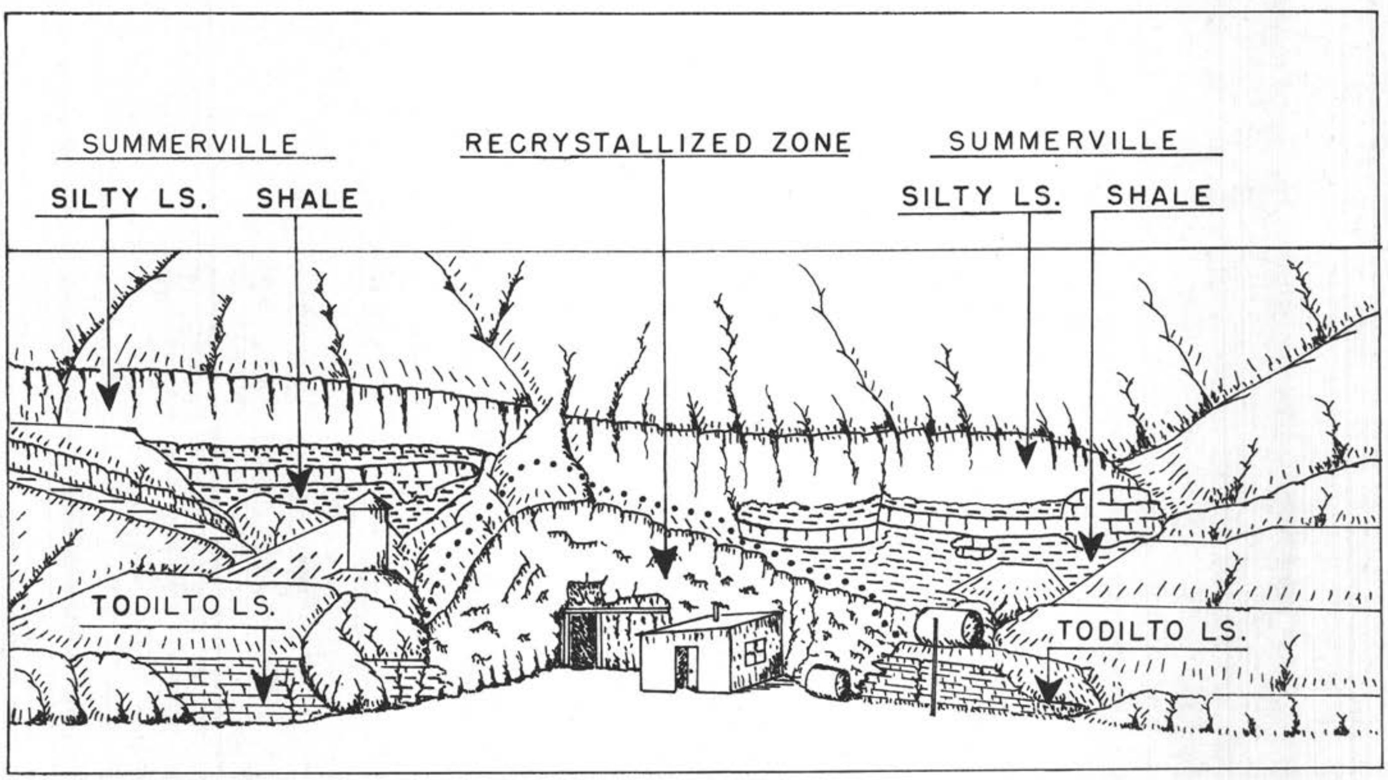


Figure 4

SKETCH OF PORTAL AREA, F-33 MINE, SHOWING RECRYSTALLIZATION OF TODILTO LIMESTONE. THE ORE BODY FOLLOWS A LONG, NARROW ZONE OF NORTHEAST-TRENDING FOLDS AND HAS BEEN FOLLOWED FOR ABOUT 1600 FEET INTO EAST GRANTS RIDGE appear to be connected. A continuous band of glass can be traced down the side of the canyon. At the time of extrusion, the glass collar and capping together probably formed an envelope around the rhyolite core.

Lithophysae are common both in the outer part of the rhyolite and in the obsidian. In the rhyolite, the lithophysae are irregular in shape and are occasionally lined with crystals of garnet, topaz, and tridymite. In the obsidian, lithophysae are about spherical and may measure as much as a foot or more in diameter. These are generally lined with tridymite and possibly cristobalite but lack garnet and topaz. Johnston (1953) reported beryl from three lithophysae in the obsidian; however, no beryl was identified by the authors.

*Peripheral perlite zone.* In addition to the perlite associated with the central dome, there is a partial ring of perlite separated from the central dome by tuff. This includes the commercial grade of perlite which is mined by the U.S. Gypsum Company (fig. 6). Banding in the quarry exposures is vertical near the center but dips steeply inward toward the margins. This fan-shaped structure is typical of many volcanic domes described by Williams and others. It demonstrates that the peripheral perlite did not flow from the central dome but is a separate vent. The peripheral perlite and the central dome are connected southwest of the quarry, and the two are probably contemporaneous or nearly so.

Flow banding in the perlite occurs on both macroscopic and microscopic scales. In the outcrop, the banding is defined by alternations of light- and dark-gray layers, while in thin-section it is characterized by alignment of microliter and elongation of pores. The banding curves around small unaltered phenocrysts of alkali feldspars. Columnar structures are observed in the perlite but not in the obsidian.

The absence of feldspar alteration and the regularity of color banding both suggest a direct intrusive origin for the perlite rather than formation by hydration of obsidian. This is further suggested by the work of Bassett et al. (1963), which shows a low air argon content in the perlite. Hydration of obsidian by meteoric water, as suggested by Friedman and Smith (1958) would be expected to introduce air argon into the perlite; this has apparently not occurred in the Grants perlite.

*Possible influence of volatiles.* On the southeastern side of the complex, the peripheral zone consists of rhyolite rather than perlite. Here also garnet and topaz are found in lithophysae. Since a volatile such as fluorine decreases the viscosity of a magma and thus promotes crystallization (Buerger, 1948),

Figure 5

AIR VIEW NORTHEAST SHOWING SLUMP BLOCKS AROUND GRANTS RIDGE. MOUNT TAYLOR ON SKYLINE it is possible that the absence of a vitreous phase and the presence of a fluorine-bearing mineral in this area are a cause-effect relationship.

## MAFIC PHASE

### PORPHYRITIC BASALT FLOWS

The earliest activity in the mafic phase of the volcanism was the extrusion of porphyritic basalt flows. These flows are 20 to 4o feet thick and were fed by central vents, one of which is well exposed close to the pumice quarry on the south side of East Grants Ridge (fig. 3). Presumably, the basalt which caps Grants Ridge was once continuous with a corresponding flow on East Grants Ridge. The basalt contains phenocrysts of plagioclase, about $An_{50}$, as much as two or three cm long, in a matrix of small plagioclase laths, olivine, pyroxene, and magnetite. In one place, octahedral crystals of magnetite approximately 2 cm across may be found in the basalt.

The basalt is younger than the felsic rocks since ( 1) it contains fragments of obsidian, (2) basalt dikes cut both tuff and perlite, and (3) one or more basalt flows are superimposed over part of the central dome.

Johnston proposed that the Grants Ridge basalts flowed southwestward down a Quaternary stream valley into the ancestral Rio San Jose near Grants. The "tadpole" shape of West Grants Ridge was interpreted as reflecting the intersection of the two streams while subsequent erosion removed the less resistant sides of the valley, leaving the basalt-covered floor as the present Grants Ridges.

### BASALT SCORIA

Several cones of red basaltic scoria protrude above the flows. These may represent the final activity of the vents which fed the flows.

### INTRUSIVE BASALTIC BRECCIA

A third mafic unit and probably the youngest igneous rock in the Grants Ridge area is the basaltic breccia plug and associated lamprophyre dikes exposed at the southwest end of East Grants Ridge (fig. 7). The breccia is an intrusive body which cuts sediments probably of the Morrison Formation. Intrusion was localized along the San Rafael fault, as shown in part by the "T" shape of the plug. Large quantities of cal-

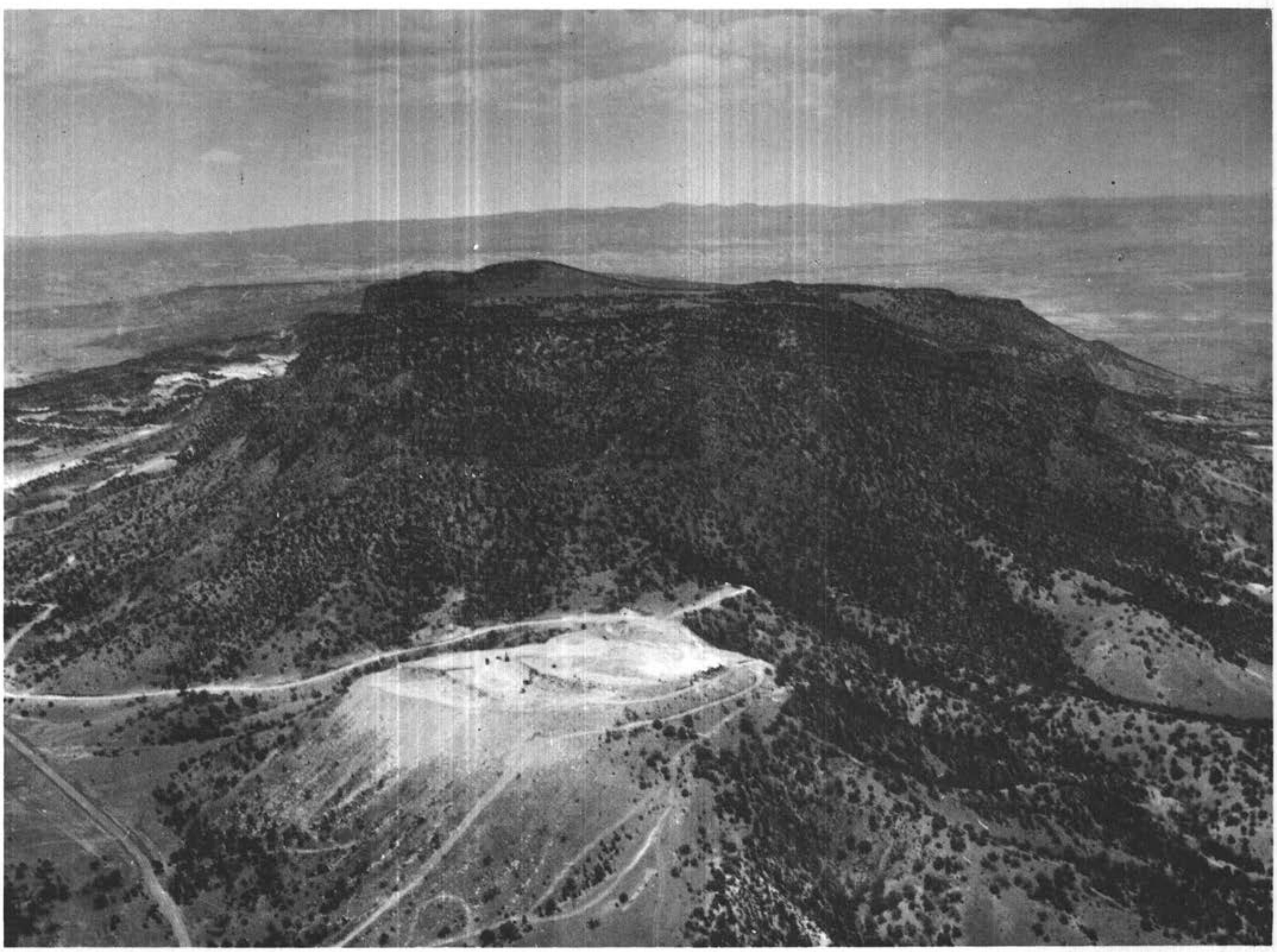

Figure 6

AIR VIEW WEST SHOWING EAST GRANTS RIDGE FELSIC COMPLEX. PERLITE QUARRY IN FOREGROUND cium carbonate from the underlying Todilto Limestone have been redistributed in both the breccia and the surrounding sediments. Quantitative chemical analyses show a progressive decrease in calcium carbonate content outward from the plug. Thinsection study shows that at least part of the calcium carbonate was deposited prior to final brecciation. Alteration of the adjacent sediments is more extensive than that associated with similar plugs in the Rio Puerco Valley northeast of Mount Taylor and is attributed to the presence of a carbon dioxide phase or anomalous amounts of water in the intruded sediments—or both.

## VOLCANISM AND URANIUM MINERALIZATION

The uranium ore body in the F-33 mine is offset by faults which probably belong to the San Rafael fault zone. The latter in turn predates basaltic igneous activity. Uranium-lead isotopic age determinations by Stieff, Stern, and Milkey (1953) suggested a minimum age of 55 m.y. for Colorado Plateau uranium ores. Uranium-lead and lead-lead ages (Miller, 1960, Columbia Univ., Ph.D. thesis) on Todilto ore from the Grants district are discordant; however, he suggested that they indicate a minimum age of 175 m.y. This is about the age of the Todilto but is inconsistent with such field evidence as replacement textures and localization of ore by small-scale folds that suggest an epigenetic origin for the ores.

Potassium-argon determinations on glasses from the perlite-obsidian-rhyolite complex (Bassett et al.) indicate an age of 3.3 to 0.3 m.y. This is consistent with field relations, which do not suggest any appreciable time lapse between the felsic and mafic phases of igneous activity. Hunt (1938) concluded on geological evidence that the earliest igneous activity in the Mount Taylor region began in late Miocene times. In summary, it appears that the uranium mineralization in the Todilto Limestone predates the East Grants Ridge volcanism and probably also predates the earliest Mount Taylor volcanism.

This study was assisted materially through support of the Division of Research and the Division of Raw Materials, U.S. Atomic Energy Commission. Much aid has also been received from local geologists and mine operators, including particularly R. D. Lynn, P. W. West, and D. F. Kittel of The Anaconda Company, B. J. Wilson and R. Youtz of the U.S. Gypsum Company, and T. 0. Evans of the Santa Fe Railway. The cooperation of the U.S. Geological Survey, Albuquerque Office, and V. C. Kelley of the University of New Mexico has also been most helpful.

Figure 7

Air view, northwest face of East Grants Ridge showing portal area of F-33 mine (on line with the peak of Mount Taylor on skyline). A breccia plug crops out in the canyon above bend in road to right

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# *Potassium-Argon Ages of Volcanic Rocks North of Grants*

W. A. BASSETT, P. F. KERR, 0. A. SCHAEFFER, AND R. W. STOENNER


## ABSTRACT

Potassium-argon age determinations on obsidian and perlite masses from Grants Mesa and La Jara Mesa northeast of Grants, New Mexico, yield ages of 3.3± 0.3 m.y. Obsidian and perlite measurements are in good agreement. Determinations on sanidine and perlite from the lower slopes of Mount Taylor give ages of 2.6 and 1.5 m.y., respectively, indicating that there are glassy flows on Mount Taylor which are the same age or younger. It was not possible to make meaningful determinations on the andesite found on Grants Mesa because of the low potassium content.


## INTRODUCTION

Grants Mesa and La Jara Mesa (fig. i) consist of volcanic rock complexes, predominantly rhyolite, capped by andesite flows. Along the northern edge of Grants Mesa, there is rhyolite, dark gray perlitic obsidian, and vitreous obsidian. These grade into one another and the vitreous obsidian typically occurs as lumps or "Apache tears" contained within the perlitic obsidian. At the northeastern end, there is a quarry in porous, light gray perlite. On the southern side, an andesitic plug pierces pumiceous tuff. Pumiceous tuffs are also exposed just under the lava capping on the southern side of La Jara Mesa. Obsidian lumps occur in this material.

The rhyolitic rocks contain between 3 and 4 percent potassium and with the exception of the tuffaceous material are suitable for potassium-argon age dating. The tuffaceous material is not suitable because of the high air (hence natural argon) content in the pores. Plagioclase from the andesite plug contains too little potassium (0.43%) to give reliable age determinations. Analytical data on the plagioclase are included, however, to illustrate the potential use of plagioclase for age dating. Because of weathering and low potassium content, very few samples suitable for age determinations were found on Mount Taylor. One glassy sample was found near the head of Lobo Canyon. It is float which may have descended from slopes farther up the mountain.

## TECHNIQUES

Potassium analyses were made by flame photometer. A11$^{4o}$ determinations were made by means of a sensitive mass spectrometer at Brookhaven National Laboratory employing the isotope dilution method. Argon was released from the samples by fusion in an induction heater. The decay constants were derived from radiochemical data by McNair, Glover, and Wilson (1956):

$$\lambda_e = 0.585 \times 10^{-10} \text{ yrs.}^{-1}$$
$$\lambda_\beta = 4.83 \times 10^{-10} \text{ yrs.}^{-1}$$
$$t_{1/2}\,(K^{40}) = 1.28 \times 10^{9} \text{ yrs.}$$
$$\lambda_e/\lambda_\beta = 0.121$$

## SAMPLE DESCRIPTIONS1

. Obsidian from Obsidian Canyon on the northern side of Grants Mesa (fig. 1). Massive, with phenocrysts of plagioclase. No apparent alteration. Numerous acicular crystals aligned in direction of flow.

2a. Obsidian lumps or "Apache tears" collected from dark gray perilitic obsidian along the northern edge of Grants Mesa. These appear to be remnants of obsidian remaining after surrounding material was altered to perlitic obsidian. Phenocrysts of plagioclase are present.

2b. Perlitic obsidian collected within inches of 2 a . Prominently oriented fracture causes it to be almost fibrous in hand specimen.

3. Porous, hydrous, light gray perlite ore from U.S. Gypsum Company quarry at the northeastern end of mesa. Plagioclase phenocrysts present.
4. Obsidian from eastern edge of mesa. Massive with sparse plagioclase phenocrysts.
5. Plagioclase from andesite porphyry plug on southern side of Grants Mesa.
6. Obsidian lumps from pumiceous tuff just under lava capping on southern side of La Jara Mesa.

7a. Sanidine phenocrysts from boulder near head of Lobo Canyon. Float which may have descended from slopes farther up the mountain.

7b. Perlite groundmass from the same boulder.

### DETERMINATIONS

Table r gives the material, location, potassium content, the amount of argon in the sample resulting from radioactive decay of potassium, and the calculated age for each of the samples described above. With the exception of Nos. 5 and 7, the determinations were essentially whole-rock analyses. The samples are homogeneous except for the minor amounts of plagioclase which merely act as diluents and do not significantly affect the results. The mean deviation for the ages of these samples (excluding Nos. 5 and 7) is ± 0.3 m.y. or ± percent.

## CONCLUSIONS

There is no apparent reason to doubt that the calculated age of 3.3 ± 0.3 m.y. is near the true age of the materials of

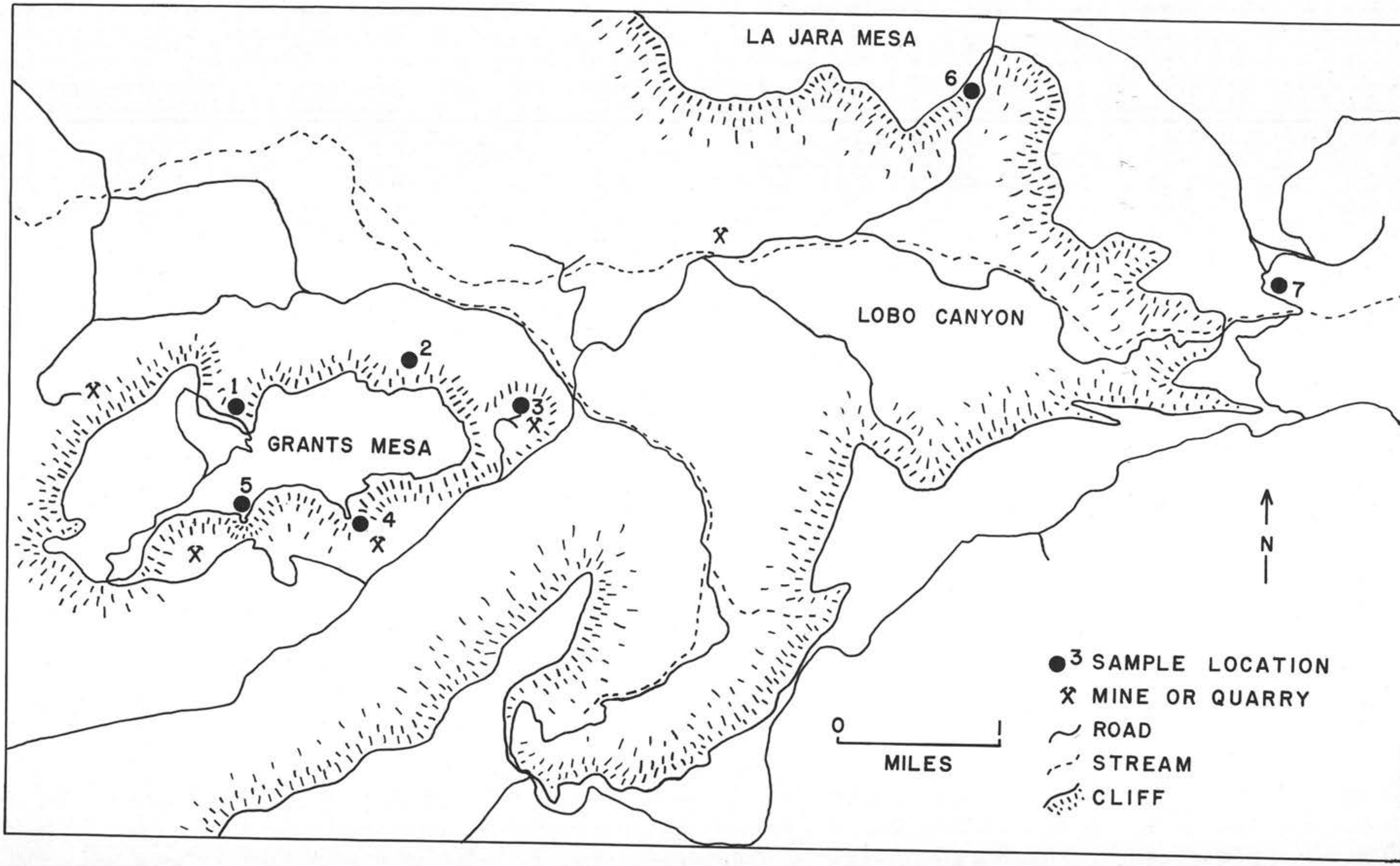


Figure 1

Location map for potassium-argon samples, covering northern portions of Grants and Lobo Springs quadrangles. The town of Grants is four miles southwest of the lower left corner of the map. The summit of Mount Taylor is one and one-half miles east of the upper right corner

TABLE 1. POTASSIUM–ARGON AGES, GRANTS, NEW MEXICO

| SAMPLE NO. | MATERIAL | % K | % RADIOGENIC ARGON | AGE (M. Y.) |
|---|---|---|---|---|
| 1 | Obsidian | 3.68 | 23 | 2.7 |
| | | | 19 | 3.1 |
| 2a | Obsidian lumps | 3.56 | 62 | 3.8 |
| 2b | Perlitic obsidian | 3.63 | 74 | 3.5 |
| 3 | Perlite | 3.72 | 33 | 3.2 |
| 4 | Obsidian | 3.60 | 42 | 3.5 |
| | | | 54 | 3.4 |
| 5 | Plagioclase | 0.43 | 10 | 9.2 |
| | | | 7 | 4.1 |
| 6 | Obsidian | 3.62 | 19 | 2.3 |
| | | | 31 | 3.2 |
| | | | 24 | 3.5 |
| 7a | Sanidine | 4.24 | 20 | 2.3 |
| | | | 39 | 2.8 |
| 7b | Perlite | 4.94 | 15 | 1.8 |
| | | | 8 | 1.1 |

rhyolitic composition in Grants Mesa and La Jara Mesa. The glassy sample from the lower slopes of Mount Taylor appears to be about the same age or younger. The high air argon content renders the perlite in this sample less reliable than the others. Attempts to date the andesite were unsuccessful but might have been successful if the potassium content had been higher or the age of the sample greater. There is no noticeable discrepancy between the determinations on obsidian and perlite, indicating that in this locality, at least, the perlite is as reliable as obsidian for making potassium-argon age determinations. It also strongly suggests that the perlite formed at the same time as the emplacement of the rhyolitic rocks.

This investigation was conducted under the auspices of the Atomic Energy Commission at Brookhaven National Laboratory and Columbia University. The authors are indebted to the U.S. Gypsum Company for permitting samples to be collected in their perlite quarry and to John Densienski for his valuable aid in making the mass spectrometric measurements. The field work was supported in part by grants-in-aid from the Geological Society of America and the American Association of Petroleum Geologists.

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# *Ground Water in the Vicinity of the Jackpile and Paguate Mines*

GEORGE A. DINWIDDIE

## ABSTRACT

Small supplies of water (5 to 20 gpm) suitable for domestic use probably can be obtained in most of the Jackpile mine area, and larger supplies of water can be obtained locally. The principal aquifers are the alluvium along the Rio Paguate in the western part of the area, the Tres Hermanos Sandstone Member of the Mancos Shale in the western part of the area, and beds of sandstone in the Brushy Basin Member and the Westwater Canyon Member of the Morrison Formation in all the area.

## INTRODUCTION

The Jackpile and Paguate mines area is in the southeastern part of the San Juan Basin, a broad structural depression in northwestern New Mexico and adjacent parts of Colorado and Utah, and is east of the Mount Taylor volcanic field. The regional dip of beds is northward to northwestward at about two degrees; however, minor faults and gentle folds vary the dips locally.

Rocks that range in age from Late Triassic to Recent crop out in or near the area, but only the rocks that range in age from Late Jurassic to Recent yield water to wells.

## BLUFF SANDSTONE

The Bluff Sandstone of Late Jurassic age is exposed in narrow to wide belts and in small patches south of the Jackpile mine near Laguna. The formation ranges in thickness from 75 to 150 feet and consists of light-colored, fine- to medium-grained, quartzose, cross-bedded sandstone.

The Bluff Sandstone yields from two to ten gpm (gallons per minute) of water of poor chemical quality to domestic and stock wells south of the mine. Larger yields have been reported; however, yields of more than ten gpm are rare.

The Bluff Sandstone has not been utilized as a source of potable water in the area because of the generally small yield and the poor chemical quality of its contained water.

## MORRISON FORMATION

The Morrison Formation of Late Jurassic age overlies the Bluff Sandstone and crops out in the valleys. The formation ranges in thickness from 300 to 500 feet and is composed of variegated shale, claystone, and discontinuous interbedded sandstone. The sandstone beds of the Morrison Formation generally range in thickness from o to 120 feet. The Recapture Member of the Morrison Formation consists of red, maroon, and greenish gray shale and claystone and interbedded sandstone. The beds of sandstone are not known to yield water to wells in the area. The Westwater Canyon Member overlies the Recapture Member and consists of a light-colored, fine- to coarse-grained sandstone. The Westwater Canyon probably interfingers with the overlying Brushy Basin Member and the Recapture Member. The Westwater Canyon yields small amounts of potable water (8 to 1o gpm) to a few wells in the area. The water produced from the West-water Canyon in one well is reported to have a dissolved-solids content of 990 ppm (parts per million). The Brushy Basin Member of the Morrison Formation overlies the Westwater Canyon Member and consists primarily of greenish gray shale, claystone, sandy claystone, and interbedded sandstone. The beds of sandstone in the Brushy Basin Member yield as much as 2o gpm of water east of the area near the Woodrow mine. This water has a dissolved-solids content of 1200 ppm. The upper part of the Brushy Basin Member consists of a light-colored, fine- to coarse-grained sandstone that, locally, is called the Jackpile sandstone of economic usage. This sandstone is variable in thickness and has a very small areal extent. Locally, it contains uranium ore. The Jackpile is not considered to be a good aquifer; however, it reportedly yields from eight to ten gpm of potable water to one well in the area. Because of lateral changes in lithologic character and thickness of beds in the Morrison Formation, the hydrologic characteristics of the beds of sandstone are difficult to predict.

## DAKOTA SANDSTONE

The Dakota Sandstone of Early and Late Cretaceous age overlies the Morrison Formation and is exposed in high escarpments along the valleys in most of the area. The Dakota consists of light-colored, fine- to medium-grained, quartzose sandstone and dark gray to black, carbonaceous shale. The unit contains a basal conglomerate at some places.

The Dakota Sandstone is not known to yield water to wells in this area and is not considered to be a good aquifer.

## MANCOS SHALE

The Mancos Shale of Late Cretaceous age overlies the Dakota Sandstone and crops out in a large part of the area. The Mancos Shale is 100 to 1500 feet thick and consists of medium to dark gray shale that contains three beds of pale yellowish brown, fine- to medium-grained sandstone in the lower part. The Tres Hermanos Sandstone Member, the three beds of sandstone and the intervening beds of shale, caps many of the mesas in the area.

The sandstones in the Tres Hermanos Sandstone Member are the only units in the Mancos Shale that yield potable water. The yield from the Tres Hermanos generally ranges from 5 to 20 gpm. Larger yields have been reported, but yields greater than 20 gpm should not be expected in this area. The Tres Hermanos contains water that has a dissolved-solids content of probably less than 1 000 ppm.

## ALLUVIUM

Alluvium of Quaternary age is exposed along the Rio Paguate and the Rio Moquino, which is tributary to the Rio Paguate. The perennial flow in the Rio Paguate above the village of Paguate is sustained by flow from springs which issue from the base of basalt of Tertiary age that caps the mesas west of the area. The alluvium along the Rio Moquino and the lower part of the Rio Paguate is not utilized as an aquifer because the water contained in the alluvium has a dissolved-solids content of as much as 2300 ppm; it may be greater at some places. However, the water in the alluvium along the upper part of the Rio Paguate is potable. Two test wells were drilled west of the village of Paguate to determine the chemical quality of the water and the rate at which the water could be pumped. One test well was drilled about one and one half miles northwest of Paguate, near the Rio Paguate. The well was 466 feet deep and penetrated alluvium, the middle and lower sandstone units of the Tres Hermanos Sandstone Member of the Mancos Shale, the Dakota Sandstone, and a bed of sandstone in the upper part of the Morrison Formation. The alluvium and the lower sandstone unit of the Tres Hermanos Sandstone Member yielded most of the water to the well. The specific capacity of this well was 0.05 gpm per foot of drawdown for a period of 12 hours. A well at this site probably could not sustain a yield of more than ten gpm. The water had a dissolved-solids content of 423 ppm and was potable. The other test well was drilled about 2000 feet west of Paguate and about 1000 feet west of the Rio Paguate, because the greatest volume of saturated alluvium was expected to be at this site. The well penetrated 60 feet of alluvium and was bottomed in the Mancos Shale at a depth of 79 feet. The alluvium at this site consists of moderately well-sorted sand with larger amounts of gravel in the lower part. Water in the lower part of the alluvium was under artesian pressure, and the water flowed at a rate of 13 gpm. Results of pumping the well indicate that the specific capacity was about one gpm per foot of drawdown for a period of 12 hours, that the coefficient of transmissibility (the rate of flow of water at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer one foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent) of the alluvium at this site was 560 gpd per foot, and that a well at this site could sustain a yield of 13 to 35 gpm. A larger yield probably could be obtained by tapping some of the underlying beds of sandstone. Water from this well contained 375 ppm of dissolved solids; the water is suitable for domestic use.

# *Ground Water in the Grants District*

EDWARD C. JOHN AND S. W. WEST

## ABSTRACT

The principal aquifers in the Grants district are the Glorieta Sandstone and San Andres Limestone of Permian age, the Westwater Canyon Member of the Morrison Formation of Late Jurassic age, the Dakota Sandstone of Cretaceous age, and alluvium and basalt of Quaternary age. Withdrawal of water from the Glorieta and San Andres has caused water levels to decline 40 to 45 feet near Bluewater and 18 to 20 feet near Grants. The New Mexico State Engineer declared the Bluewater Underground Water Basin in May 1956 to stop additional development of water in that area.

The transmissibility of the aquifer in the Glorieta and San Andres ranges from about 25,000 to 3,000,000 gpd per foot. The yields of wells that tap this aquifer range from 10 to 1100 gpm. The average specific capacity is 200 gpm per foot of drawdown.

The Westwater Canyon Member furnishes most of the water supply near Ambrosia Lake. Large segments of the Westwater Canyon have to be drained to mine the uranium ore, but much of the mine water is used in processing the ore. Total pumpage from the Homestake—Sapin Partners Section 25 mine was 2.6 billion gallons from August 1957 to January 1963, and the pumpage from the Section 23 mine was one billion gallons from February 1958 to January 1963. Water is being pumped also from 11 other mines in the area.

The Dakota Sandstone is used as an aquifer less than the Westwater Canyon Member, because larger supplies of better quality water can be obtained from the Westwater Canyon Member.

Wells that tap the alluvium and basalt yield as much as 1000 gpm of water to wells between Bluewater and Milan.

The water in the San Andres Limestone contains 35o to 75o ppm of dissolved solids in the southwestern part of the Grants—Bluewater Valley and as much as 2200 ppm of dissolved solids farther from outcrops. Water in the Westwater Canyon Member contains an average of about 600 ppm of dissolved solids in the vicinity of Ambrosia Lake and is the best water in that area. The quality of water in the Dakota Sandstone generally is not so good as that in the Westwater Canyon. The concentration of dissolved solids in water from the alluvium and basalt ranges from 135 to 5500 ppm. The water of best quality in the alluvium and basalt is between Bluewater and Milan.

## INTRODUCTION

The Grants district is in southeastern McKinley and north-central Valencia counties, New Mexico, an area underlain by the most extensive proved uranium deposits in the United States. Large supplies of ground water have been necessary for the processing of the uranium ore; yet, the occurrence of extensive deposits of ore in the zone of water saturation has been a difficulty in mining.

The altitude ranges from about 6500 feet at Grants to an average of about 7100 feet near Ambrosia Lake. The climate is arid to semiarid and the average annual precipitation is about ten inches, much of which falls during thunderstorms in July, August, and September. All the streams in the area are intermittent and are sediment-laden during the short periods of storm runoff.

The sole source of water supply for the area is obtained from underground reservoirs, except for occasional small diversions of irrigation water from Bluewater Creek. Ground water was used primarily for irrigation in the valley between Grants and Bluewater and for domestic and stock supplies elsewhere prior to the processing of uranium in 1955. Water use since 1955 has changed radically, and in 1962, mills for processing uranium ore and other industries, trailer camps, housing developments, and municipalities used nearly half the water pumped.

Withdrawal of large amounts of ground water in the Grants area has caused water levels to decline greatly since regular measurements of water levels began in 1946. North of Bluewater, levels have declined 4o to 45 feet, and from Bluewater southeast to near Grants, the levels have declined 18 to 20 feet.

The Bluewater Underground Water Basin, which lies in T. 9-12 N., R. 9-11 W., was declared by the State Engineer on May 21, 1956 (New Mexico State Engineer Office, 1958) to regulate the amount of ground water used. Industrial and municipal use of ground water in the declared basin has increased each year since 1951, but only by converting irrigation rights to industrial and municipal rights. The total amount of ground water pumped in the basin each year since 1951 has remained almost constant at about 13,000 acre-feet a year. Three uranium mills and supporting facilities were supplied in 1962 with water from wells in the declared basin.

The Geological Survey in cooperation with the State Engineer of New Mexico began a program of water-level observations and hydrologic studies in the Grants—Bluewater area, primarily in the irrigated part, in 1946. An intensive study of ground water in that area was begun in 1954 and completed in 1957 (Gordon, Reeder, and Kunkler, 1961).

Much of the uranium ore in the vicinity of Ambrosia Lake is below the water table and both mine drainage and disposal of water are problems. The disposal of mine water and of waste water from milling operations in a manner to preserve the potability of underground waters has been given much attention by the mining companies.

A study of the ground-water hydrology of southeastern McKinley County was begun by the U.S. Geological Survey in cooperation with the New Mexico State Engineer in 1957 to evaluate the waste-water disposal problem and to obtain information on the general availability and quality of ground water in the vicinity of Ambrosia Lake.

Many contributions to these studies were made by land owners in the area, well drillers, civic leaders, and mining companies who furnished information on wells, water use, and subsurface geologic and hydrologic conditions in mines. Their cooperation is gratefully acknowledged.

# GROUND WATER

The principal aquifers, in ascending order, are the Glorieta Sandstone and San Andres Limestone of Permian age, the Westwater Canyon Member of the Morrison Formation of Jurassic age, the Dakota Sandstone of Cretaceous age, and alluvium and basalt of Quaternary age *(see* geologic map of area). Aquifers that yield smaller supplies of water include rocks of the Chinle Formation of Late Triassic age and the San Rafael Group of Middle or Late Jurassic age. The Glorieta Sandstone is the oldest formation described, because the Glorieta and some of the younger rocks yield more water of better chemical quality than the rocks older than the Glorieta.

## SAN ANDRES LIMESTONE

The San Andres Limestone and the underlying Glorieta Sandstone crop out on the flanks of the Zuni Mountains and underlie all the area; together they form the principal aquifer in much of the area. Solution channels and cavernous zones have developed in the San Andres, so that the transmissibility of the limestone is great at most places, ranging from about 25,000 to 3,000,000 gpd per foot (gallons per day per foot). Upward flow from the underlying less permeable Glorieta is induced when water is withdrawn from the San Andres. Wells that tap the San Andres in the Rio San Jose Valley range in depth from 100 to 980 feet, and the depth to water in them ranges from 20 to 250 feet. The yields range from 500 to 2800 gpm (gallons per minute), and the specific capacities range from 10 to 1100 gpm per foot of drawdown. The average specific capacity is z00 gpm per foot of drawdown.

Two exploratory wells are known to have penetrated part of the San Andres Limestone near Ambrosia Lake. A well 3388 feet deep was drilled by the Phillips Petroleum Company in the SE1/4 sec. z8, T. 14 N., R. 9 W. for emergency use at the company's uranium ore-processing mill. Another well, 3086 feet deep, was drilled by Kermac Nuclear Fuels Company in the SE1/4 sec. 22, T. 14 N., R. 0 W., but it was plugged soon after it was drilled because adequate supplies of water were obtained from other sources. The water was under artesian pressure and rose to within 600 feet of the land surface. Pumping rates of as much as 300 gpm and a draw-down of about 600 feet have been reported for these wells.

## CHINLE FORMATION

Sandstone beds in the Chinle Formation yield small amounts of water to domestic and stock wells in the Grants area. However, the sandstones are relatively impermeable and few wells tap this aquifer in the area, because better aquifers can be tapped at most places.

## SAN RAFAEL GROUP

The San Rafael Group of Jurassic age consists of the Entrada Sandstone, the Todilto Limestone, the Summerville Formation, and the Bluff Sandstone. Water for domestic and stock use is pumped locally from the Entrada in areas adjacent to its outcrops *(see* geologic map). The Todilto Limestone in the Westvaco mine shaft has yielded as much as 35o gpm. However, it generally is not used as a source of water supply. The Summerville Formation has not been utilized for ground water. The Bluff Sandstone west of Ambrosia Lake is structurally high and several wells are finished in this formation. Pumping rates of 10 to 45 gpm were reported for these wells.

## MORRISON FORMATION

The Morrison Formation in this area has been divided into the Recapture Shale, Westwater Canyon Sandstone, and Brushy Basin Shale members. Only the Westwater Canyon yields significant supplies of water. The Westwater Canyon Member is an intensely developed aquifer in the vicinity of Ambrosia Lake, but it has not been used as an aquifer in the vicinity of Grants because better aquifers are available. The Westwater Canyon consists of arkosic sandstone, deposited in part as discontinuous channel sands trending east-southeasterly, and minor amounts of mudstone. Sorting is poor in the coarser sands but improves as the grain-size diminishes (Granger et al., 1961, p. 1, 185). The hydrologic properties of the Westwater Canyon, consequently, vary widely in short distances.

The Westwater Canyon Member has a variable thickness because it intertongues with the underlying Recapture Shale Member and the overlying Brushy Basin Shale Member. Granger et al. (p. 1, 185) reported that the Westwater Canyon ranged in thickness from 30 to 270 feet. The depth to the top of the Westwater Canyon in the vicinity of Ambrosia Lake averages 750 feet but ranges between 300 and 1500 feet. An upper sand unit of the Westwater Canyon has been locally called the Poison Canyon Sandstone (Zitting et al., 1957, p. 55) and is separated from the main body of the Westwater Canyon by as much as 40 feet of Brushy Basin.

Mining of uranium ore from the Westwater Canyon Member started in deposits above the regional water table. The ore deposits extended beneath the water table, so that the major companies had to expend considerable effort to determine the conditions that would be encountered when mining began below the water table. A series of test wells was drilled and test-pumped to determine the coefficients of permeability, transmissibility, and storage. A homogeneous aquifer necessarily was assumed for computing these coefficients. Later, when shafts were dug, the sandstone did not yield so much water as had been indicated by the pumping tests, because the vertical permeability apparently was less than the horizontal permeability. The difference in vertical and horizontal permeability was attributed to beds of shale between the beds of sandstone (Stoehr, 1959, p. 49). Much of the permeability is along joints in the sandstone; a drift may be relatively dry, intersect a joint, and begin to produce water. The rate of water production is related also to the static head of water above the drift.

Friable wet rock that tended to spall and cave, wet muck, and sanding of sumps, and the fact that drained rock has greater strength than wet rock made it advisable to drain the area to be mined as completely as possible. The method of draining is to construct a drift under the ore body and drill holes in the walls to provide channels for water drainage. The discharge is kept at a semiregulated amount by controlling the footage of drifts and drill holes so that water production does not tax the pumping plants (Stoehr, p. 46 and 50; C. E. Doney, Phillips Petroleum Company, oral communication, 1962). Perched water, where present above clay beds, commonly creates a problem of draining ore bodies that lie above zones previously drained (C. E. Doney, Phillips Petroleum Company, oral communication, 1962). Pumpage from individual mines in the area ranges from less than z00 gpm to more than 000 gpm.

Records of Homestake—Sapin Partners show a total pumpage from the Section 25 mine of about z.6 billion gallons for the period August 1957 to January 1963 and from the Section 23 mine about one billion gallons for the period February 1958 to January 1963. Water is being pumped from 13 mines currently in operation in the area.

### DAKOTA SANDSTONE

The Dakota Sandstone of Early and Late Cretaceous age is composed of fine- to coarse-grained sandstone and carbonaceous shale. Mine shafts in the Ambrosia Lake area are reported to have water yields ranging from 1 0 to 120 gpm from the Dakota. However, the Dakota Sandstone is little used as an aquifer in the Ambrosia Lake—Grants area because larger yields of better water can be obtained from the Morrison Formation at slightly greater depth than the Dakota. The water in the Dakota Sandstone is confined under artesian pressure by the overlying impervious Mancos Shale in broad areas near Ambrosia Lake.

### ALLUVIUM AND BASALT

Alluvium and basalt of Quaternary age form an aquifer of secondary importance near Grants. Wells that tap the alluvium and basalt aquifer range in depth from 30 to 370 feet and the depths to water in them range from 10 to 120 feet. The aquifer yields as much as 1000 gpm of water to wells. The largest yields are obtained in the vicinity of Bluewater Station and Milan.

In the Ambrosia Lake area alluvium is mostly clay and silt which contains little or no water.

## QUALITY OF WATER IN THE PRINCIPAL AQUIFERS

Water in the San Andres Limestone is high in calcium, magnesium, sulfate, and bicarbonate, except near the recharge areas. A strong odor of hydrogen sulfide gas makes the water objectionable for domestic use in the vicinity of Ambrosia Lake. The water of best quality, containing 350 to 750 ppm (parts per million) of dissolved solids, in the San Andres is in the southwestern part of the Grants—Bluewater Valley. The concentration of dissolved solids is as much as 2200 ppm at some places in the area. Water in the Westwater Canyon Member of the Morrison Formation has a dissolved solids concentration averaging about 600 ppm in the vicinity of Ambrosia Lake and is the best water sampled in that area. Some analyses show as much as 1400 ppm of dissolved solids, which fact suggests contamination from other sources, possibly from the Dakota. Most of the dissolved solids are sodium, sulfate, and bicarbonate. Water from the Westwater Canyon Member most nearly meets the requirements of all uses of water in the Ambrosia Lake area.

The quality of water from the Dakota is not so good as that from the underlying Westwater Canyon Member. This probably is due to beds of carbonaceous shale in the sandstone. The dissolved solids are mainly sodium, sulfate, and carbonate, and they average about 1400 ppm.

The quality of water in the alluvium and basalt varies widely within short distances and within short periods of time because the sources of recharge are numerous and they may contribute water of different quality at different times. The concentrations of dissolved solids in water from the alluvium and basalt range from 135 to 5500 ppm. The water of best chemical quality (450 to 500 ppm dissolved solids) is obtained from the alluvium and basalt between Bluewater and Milan, where the largest average yields also are obtained.

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# *Uranium Logging Techniques*

W. A. LINTON

## INTRODUCTION

Early uranium exploration techniques ranged from aerial scintillation surveys over vast areas to the use of hand-sized counters searching outcrops. Invariably, the indicated radioactive anomalies required a drilling process to investigate the potential uranium areas. Core drilling was expensive and time-consuming and hand-reel-operated in-hole detectors, using a meter deflection as the determinate, had personal limitations. A major contribution was truck-mounted equipment, capable of permanently recording in-hole gamma-ray, resistance, and self-potential information.

Drilling and logging activity flourished, particularly from 1956 through 1958, from Gallup, New Mexico, to the Rio Puerco, west of Albuquerque. As many as six contracted uranium logging trucks stayed busy on a relatively constant basis 24 hours a day, seven days a week. With the sinking of mine shafts and subsequent underground development, it was necessary to have gamma-ray information from the mine long holes; and from this, a compact portable instrument was developed to record gamma-ray data on a strip chart. Throughout the development of uranium operations, quantitative interpretation of gamma-ray logs has maintained a place of greatest importance.

## BORE-HOLE MEASUREMENTS

The gamma-ray log in uranium exploration is used practically exclusively for locating radioactive zones suitable for mining uranium, but it will be noted that the gamma log resembles the S.P. curve in distinguishing sandstones and shales (fig. 3). The prime value of a gamma-ray log prior to uranium mining interest was its use in cased holes for obtaining a sand-shale relationship since it was impossible to obtain electric logs.

Century Geophysical Corporation conducted an experimental spectral program using a scintillation instrument with hopes of making in-hole "signatures" that would measure the relative daughter products of the uranium decay series, thus providing a way to determine the equilibrium of uranium ore. The different energy levels of each radioactive daughter product can be distinguished under laboratory conditions, but the in-hole spectral response was dist0rted. Lower energy gamma-rays were absorbed and excessive back-scattering effect could not be overcome.

Much has been written regarding the interpretation of S.P. and resistance curves. Briefly, the S.P., or spontaneous potential log, generally indicates the presence of formation permeability. Natural currents flow between contacts of contrasting media, as between shale and permeable beds. As these currents move from shale through the bore hole to the sand and into the shale again, the greatest potential difference is at the sand-shale interfaces, and this is measured in the mud column by the logging tool. Usually, the S.P. curve has a shale base line of low resistivity corresponding to the impervious formation as seen in the Mancos Shale. Deflections to the left (negative) indicate permeable beds; however, the magnitude of the S.P. deflection is not necessarily a direct relationship as to formation permeability.

The best logging instrument for formation identification and correlation is a single electrode resistance tool. The resistance log shows the relative conductivity between sandstone and shale, but its limited depth of formation penetration eliminates its use as a quantitative parameter for true resistivity measurements. In thin formations the monoelectrode gives outstanding detail and in thick formations the trace is not distorted; thus, bed boundaries are easily determined.

## INSTRUMENTATION

It is known that Geiger counters (and crystal detectors) have a definite interval following each response to radiation pulses when the counter is not sensitive to additional pulses. This interval is referred to as coincident loss or "dead time." This means that at high counting rates the response of the detector is nonlinear. Over-all instrument response time is related primarily to the dead time of the paralleled group of Geiger tubes and to cable impedance, which limits the pulse width triggering the counting rate circuit. Once the instrument dead time has been determined, observed counts can be corrected to true counts by the following relationship:

$$N = \frac{n}{1 - nt}$$

where N = true counts, n = observed counts, and t = dead time in microseconds.

The truck-mounted equipment has an approximate dead time of 60 microseconds and the mine equipment has an approximate response time of 25 microseconds. This means that it is only in the higher ore ranges above 0.40 percent equivalent $U_3 0_8$ where instrument dead time is appreciable (5% variation). This dead time loss is not ignored; rather a correction is made because of this condition as shown on the conversion curve (fig. 5).

The Geiger tubes used in the uranium l0gging are halogen-quenched to give a desirable combination of long life, large pulse output, electrical ruggedness, and insensitivity to temperature. Periodically, the Geiger probes are intercompared at various radiation intensities to assure reproducibility of each other by placing a i 0-millicurie radium source needle at predetermined distances relative to the probe. These comparisons show that, up to 4300 counts per second or up to a grade equivalent of 0.70 percent $U_3 0_8$ for mine equipment (higher grade for surface instrumentation), the maximum differences between probes are within a mean of 3.5 percent. At counting rates simulating much greater than 0.70 percent equivalent $U_3 0_8$, a maximum difference within a mean of 0.5 percent was noted. Variations of this magnitude are to be expected. Comparison logs made by several units in the same bore hole (with less than 0.70 percent equivalent $U_3 0_8$) indicate an

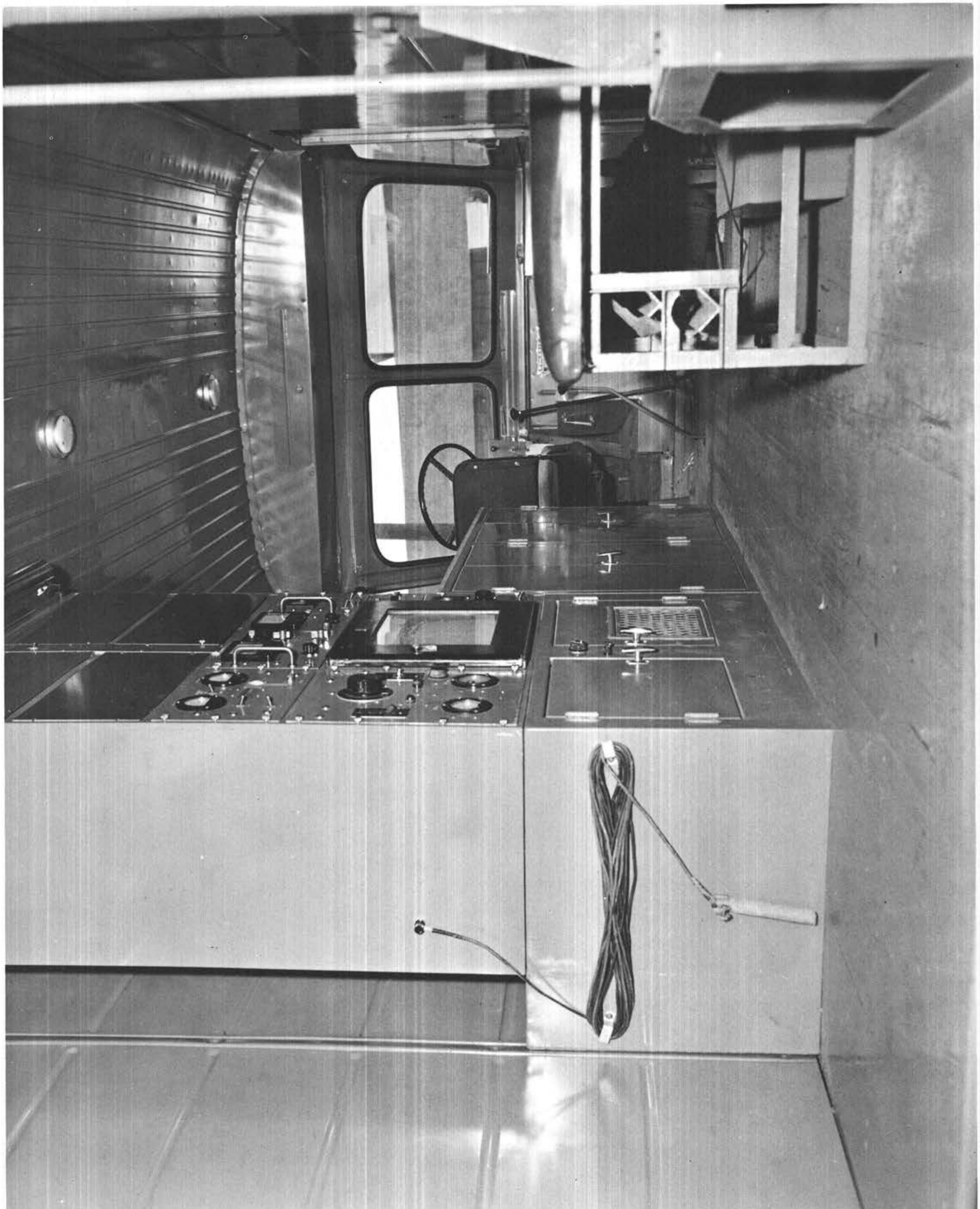

Figure 1

Inside of truck-mounted unit

over-all reproducibility between units within a mean of 5 percent. From this, it can be seen that another 1.5 percent instrumental variation is apparent. This results from the limited degree to which a radioactive source can be calibrated to its known intensity level and to the limited extent that gamma scale decade positions can be established precisely for each unit.

The truck-mounted logging system, Model 2201 (fig. 1), consists of a probe housing a seven-tube Geiger detector bundle; a D.C. power supply for the probe; a surface-regulated power supply of 30o volts; a measuring panel with controls for adjusting scales of the gamma-ray; resistance and self-potential channels; and a dual strip chart Brown recorder. Power is supplied from a 2.5-KW, 6o-cycle IIo-volt, A.C. generator driven through a power take-off from the truck engine. This generator supplies power for an electric motor-driven cable hoist and the electronic instrumentation. The resistance and gamma-ray signal is telemetered over a single conductor armor cable and at the surface; the two signals are separated and fed through amplifiers, pulse shapers, and counting rate meters to a dual recorder. A cable measuring sheave provides depth measurements by means of a selsyn drive to the recorder.

All radioactive zones of interest are "rerun" on an appropriate gamma scale at a speed of five feet a minute with a time constant of two seconds. This method statistically assures adequate recording of gamma radiation over the full range of the higher counting rates so that there is maximum definition of changes in ore grade.

The mine logging instrumentation, Model 2400 (fig. 2), is housed in a compact, watertight, aluminum box with a rubber gasket clamp-type, plexiglass cover, which enables viewing of the recorder. This unit is powered by eight, 1.3-volt, rechargable, dry, nickel-cadmium batteries which power the probe, count rate meter, and the servopotentiometer type recorder. The over-all weight of this equipment is 24 pounds. The probe houses five Geiger tubes, a transistorized pulse discriminator circuit, and a high-voltage supply using a pulse-type oscillator. The transistorized count rate meter consists of a discriminator potentiometer, emitter follower, pulse shaper, and diode counting circuit, with eight stages ranging from loo cps to 20,000 cps.

By narrowing the pulse width as the count rate increases, dead time is kept to a minimum throughout the 2o,000-cps range. This diode pump circuit is widely used in precision nuclear and radar applications. The recorder utilizes two printed circuit plug-in boards, one for the voltage amplification stages and one for the power amplifier stages. A voltmeter is provided for readily noting battery voltages.

Under mine operating conditions, utilizing a two-man crew, a probe is pushed into long holes (up to 200 feet) by using five-foot fast coupling and 3/4-inch-diameter aluminum poles. The log is obtained when the probe is withdrawn from the hole by the cable turning a measuring wheel that is geared to advance the chart paper. Positive identification of gamma-scale positions are determined by adopting a standard operating procedure.

A crew can readily log 1600 feet during an 8-hour shift. This is done on a service basis by men thoroughly familiar with all the mine workings. Log write-up and interpretation is performed the following day and the radiometric information is submitted on the logs in terms of percentage $U_3O_8$ for a given thickness (fig. 4).

## GAMMA-RAY CALIBRATION

Gamma-ray logs are only as good as their radioactive calibrations. The following measures are necessary to insure reliability of gamma-log calibration:

(1) A known Bureau of Standards radiation source is referred to a detector probe at a definite position and at a given distance. This absolute calibration then relates microroentgens or gamma-ray intensity to a convenient term, such as counts per second or chart deflection.

(2) Sealed stabilized radiation sources (radium salts) are then referred to the same gamma intensity and their values are recorded on the source itself. All sources are constructed to be within plus or minus two percent of each other. Exact positioning of this source relative to the probe detecting device should be a simple operation for subsequent field calibrations. A convenient design is a cylindrical "slip over" source that surrounds the detector on all sides and locates the source directly over the detector by positioning against the base of the probe.

(3) The sources are then used in normal operating procedures to insure that the instrument is in proper adjustment. Calibrations are always recorded graphically on each surface hole logged. In mine logging, with portable equipment, graphic calibrations are made before and after logging in a specific mine location.

(4) Each month the gamma field sources are intercompared. Should a source have changed, this monthly reference would show the discrepancy and the source would be taken out of service. This rarely occurs and only gradual changes are noted.

(5) Every six months an absolute calibration is obtained with an operational source in terms of the Bureau of Standards radiation reference.

Since it is necessary to record over a range of at least 2000 times, five different radiometric scales (500, 100o, 2500, 5000, and 10,000 cps) are used in actual logging practice. The source calibrations are made on each of the scale positions. A special case arises with gamma logging in the mines where the background radiation varies from place to place. The source housing of the radium salts is made of brass so that background radiation is somewhat shielded from the probe. Early in our mine operations, empirical observations were recorded and plotted relating gamma radiation background to background, plus a regular calibration source. This predictable background response information was then tabulated and placed on each instrument so that calibrations can be verified at the time they are made. In extremely high background areas, an inversion of radiation response is noted when the source is placed in position for calibration because of the shielding effect of the source holder.

## GAMMA-RAY LOG INTERPRETATION

The quantitative interpretation of gamma-ray logs as described in this paper are modifications of the precision type

Figure 2

MINE LOGGING EQUIPMENT IN OPERATION

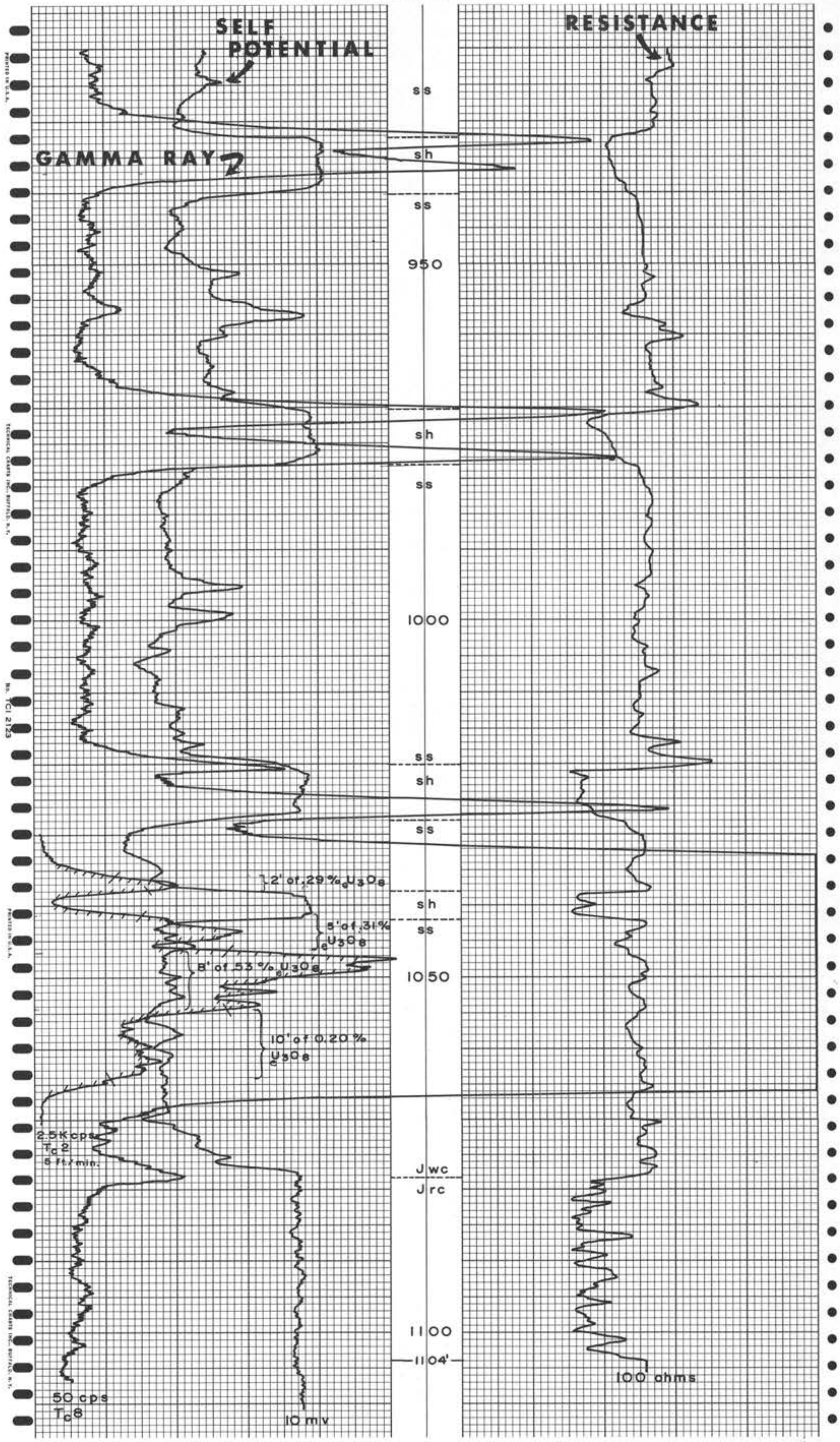


Figure 3

SURFACE LOG

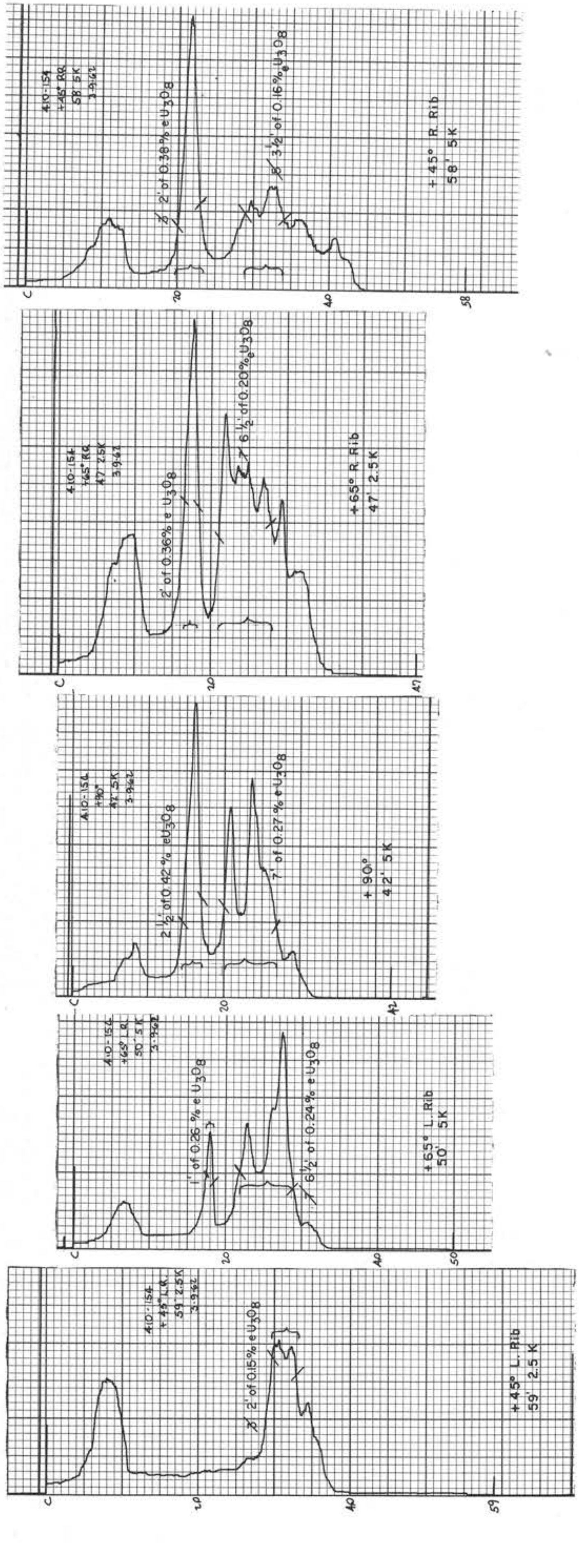


Figure 4

MINE GAMMA-RAY CORRELATION AND INTERPRETATION

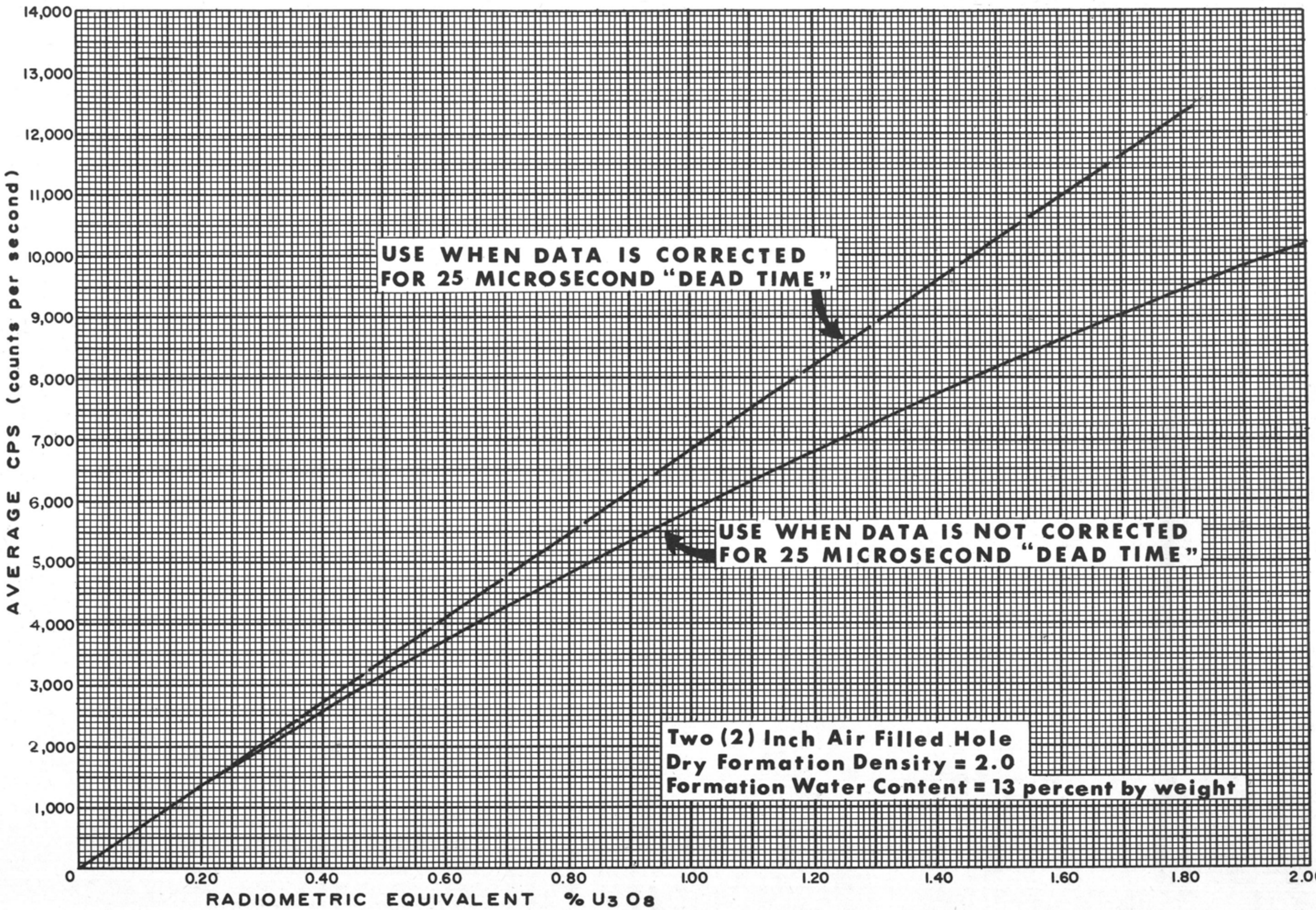


Figure 5

RELATION BETWEEN COUNTS PER SECOND AND RADIOMETRIC EQUIVALENT PERCENT $U_3O_8$. (FOR CENTURY GEOPHYSICAL CORP. PORTABLE (MINE) LOGGING UNIT—MODEL 2400) method as described by Scott et al. (1961). Conversion overlays in terms of equivalent $U_3O_8$ were not employed by Century because there exist modifications in interpretation methods of each party engaged in uranium evaluation which would preclude the use of only one overlay conversion system.

The response to radioactivity of Century's gamma-ray logging unit, truck-mounted Model 2201 and portable Model 2400 (mine unit), was related to the equivalent $U_3O_8$ values in simulated bore holes constructed by the U.S. Atomic Energy Commission in Grand Junction, Colorado. These data were also substantiated by gamma-ray logs as related to chemical core analysis from holes core-drilled in the Ambrosia Lake area of northwestern New Mexico, although original conversion data (prior to 1958) were determined from core-hole data alone in the Grants district. The simulated bore-hole method for radiometric conversion is more reliable than core-hole comparisons in that the in-hole volume of gamma radiation influencing the logging equipment is approximately 500 times more representative of the ore zone than a two- or three-inch core sample. As related by Broding (1959), the zone of influence of a radioactive detector is roughly a spheroid three feet in diameter. The greater the heterogeneous nature of the ore, the greater the error induced by radiometric core comparisons, and the variations that result from these irregularities can best be minimized by increased statistical sampling and comparison.

Early gamma-ray radiometric interpretation used a maximum deflection method. Random distribution of ore grade within an anomaly and other factors limit this method to only a semiquantitative radiometric determination as described by Droullard and Dodd (1958). Current gamma-ray interpretation by Century utilizes an integral method using "cut-off deflection" or "grade cut-off" method for thick ore zones (five feet of thickness). Ore zones with five feet of thickness or more are digitized in terms of counts per second at one-foot intervals. The sum of the intervals is divided by the thickness to arrive at average counts per second for a given thickness. By referring the average count to a percentage equivalent $U_3O_8$ from a curve (fig. 5), the information can be written on the log (fig. 4; the crossed-out numbers in this figure represent the thickness as shown from the log and the inserted numbers represent the true thickness with regard to hole angularity). Generally, the individual "log picks" are not corrected for "dead time," but are referred to the non-"dead time" conversion curve (fig. 5). This is not absolutely correct, but the percentage error using this method is negligible. Where there are major changes in radiation intensity (a factor of 2) for substantial thicknesses (four feet), the zones are subdivided (fig. 3) so that one average counts-per-second value per thickness interval is representative for a correction conversion.

For thin ore horizons (four and one-half feet or less), data are integrated at each half-foot interval and a "tail effect" is considered significant for a distance of one quarter of a foot on each side of the bed boundary. In very thin ore horizons, this can give an average value greater than the peak deflection of the gamma-ray log. This is valid when we consider the increased flux which is measured in a thick ore zone (one of effective infinite thickness as described by Droullard and Dodd) compared to a thin ore zone of the same grade. The maximum gamma response will be less in thin ore zones (fig. 6), and this apparent discrepancy is compensated by utilizing

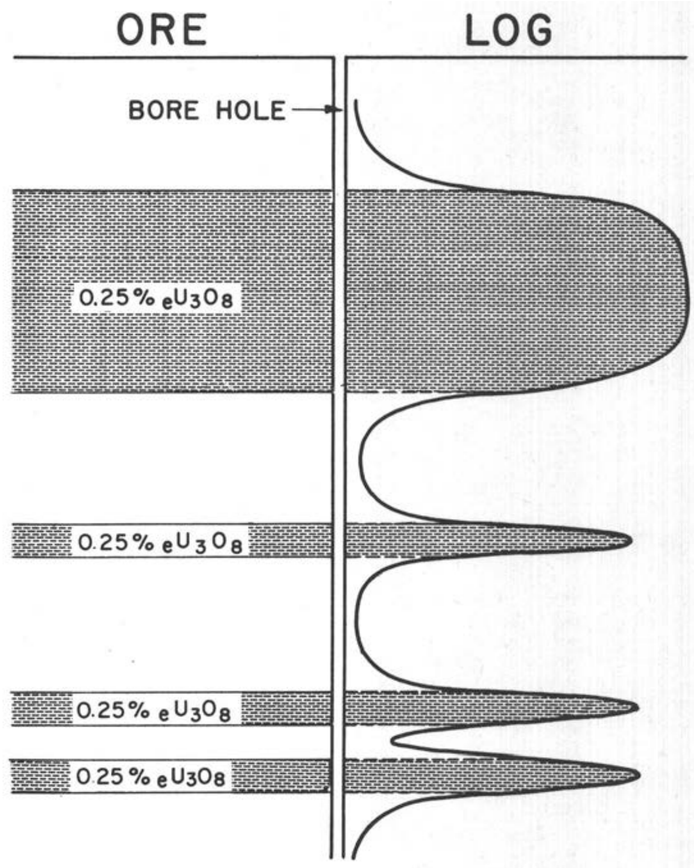


Figure 6

SCHEMATIC GAMMA-RAY RESPONSE FOR VARIOUS BED THICKNESSES

the "tail effect" or the radiation which the detector measures at the proximity of the ore zone. For thick ore zones (five feet or more), the "tail areas" are evident, but the over-all effect on the integrated area under the thick anomaly is insignificant.

Perhaps any objection to an arbitrary grade cut-off method, or the limitation of the tail effect to only one quarter of a foot on each side of the bed boundary, can be rationalized when one considers that a very large percentage of all underground long holes intersect the lenticular ore zones at acute angles. As a result, the gamma-ray flux masks a distinct ore boundary determination. For a given ore zone, the grade will be lowered by choosing a thicker interval, and selecting a lesser thickness will increase the grade so that the grade products of the two are nearly the same. Generally, a grade cut-off is established on the gamma anomalies of 0.15 percent equivalent $U_3O_8$, and the 0.10 to 0.15 percent equivalent $U_3O_8$ interval is interpreted separately.

Regarding bed boundaries in terms of distinguishing significant responses, a study was made to evaluate the relative merits of Geiger tube and scintillation crystal detectors. Comparisons were made using a seven tube Geiger Bundle, a 3/4" x 1" Nal/TI crystal, and the same crystal collumated with 1/2-inch thickness of lead utilizing a 1/4-inch portion of the crystal exposed to gamma radiation through aluminum. Test runs were made in the U.S. Atomic Energy Commission simulated bore holes at Grand Junction, Colorado (fig. 7). It

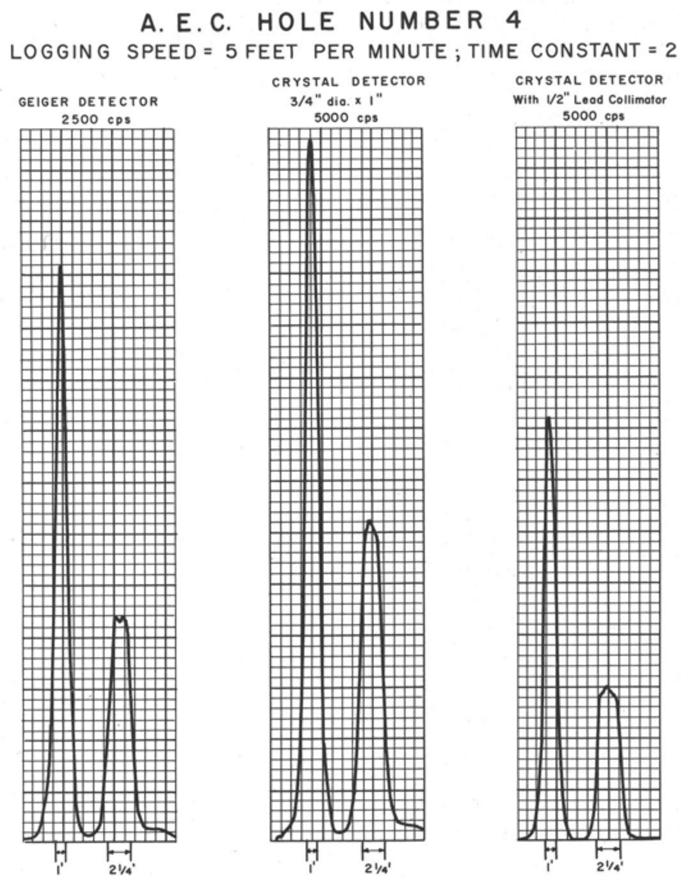


Figure 7

COMPARISON OF GEIGER DETECTOR AND CRYSTAL DETECTOR FOR BED THICKNESS DETERMINATION

is apparent that the configuration of the radioactive response indicates that each detector type is comparable to the other. As expected, the crystal detector shows higher counting rates as evident in the increased amplitude on a higher gamma-scale position of both the shielded and unshielded curves.

## HOLE DEVIATION

Late in 1957, it became apparent that ore reserve calculations and mine planning were appreciably affected by deviated surface drill holes. Early exploration work was only concerned with getting holes drilled that would indicate the presence of uranium. Shallow ore horizons (200 feet), intermediate, as well as deeper (1500 feet), ore bodies were affected by information derived from "crooked holes." Deviations of 3o feet of horizontal displacement are not uncommon in 200-foot holes, and with hole spacing on 25-foot centers, the magnitude of error in mapping and mine planning is apparent. Deeper holes (fig. 8) show as much as 352 feet in horizontal displacement at a depth of 875 feet. This is an extreme example; however, deviations in the order of 100 feet are numerous. Generally, inclination angles are less than 10 degrees, but the inclination angles on the hole represented reach a maximum of 41 degrees from vertical. The over-all vertical loss is 101 feet.

Originally, deviation data were obtained from a single photographic picture of a magnetically oriented compass and a clinometer reading. This instrumentation was suspended in a 10-foot-long brass barrel aligned along the wall of the hole. Techniques today employ a multishot photographic film type of survey. Data are recorded on 10-millimeter film at 50-foot-depth intervals and at a time interval of one minute for each depth point. A timing mechanism actuates self-contained batteries to make a film exposure of the inclination angle as related to the magnetic compass. After the film is developed, a projector is utilized to magnify the pictures for readings and subsequent calculations.

It should be mentioned that current drilling techniques, that is, use of drill collars and reduced weight on the bit, have lessened the amount of hole deviation. In areas where directional hole data are not obtained, it can be reasonably assumed that holes will deviate in an updip direction.

Hole deviation is pronounced in underground long-hole drilling. This seems to be related to the high speed of the rotary-type drills. The holes, in practically every instance, deviate in a clockwise direction with the rotation of the bit. Generally, those holes collared greater than 20 degrees above horizontal will migrate up. Those holes drilled less than 20 degrees above horizontal and those below horizontal may deviate up or down; thus, formation lithology evidently exercises more control on the lower angle holes. Long-hole data are plotted in plan view and in cross section (fig. 9). The clockwise rotation of these holes is so pronounced that actually a complete fan cross section of holes 13o feet in length or longer is representative of a cross-section plane 45 degrees from the direction of the drift. Where directional information is lacking, ore sills are established from vertical holes or high-angle holes that are drilled sublevel.

Directional instrumentation is the same for underground holes as that used on the surface. The barrel housing the instrument is 1 3/8 inches in diameter and 4 1/2 feet long. This dimension is larger than desirable for 1 3/4-inch diameter holes, and there have been occasions when the curvature of the hole was so acute that the directional barrel would jam. Subsurface directional data are obtained at either 10- or 20-foot intervals.

## CONCLUSION

Elaborate logging equipment is used in petroleum exploration, but these systems are devised to quantitatively determine the nature and percentages of the fluids which fill the pore spaces of the rock. It appears unlikely that any of these investigations would prove of more importance than the response of a natural gamma-ray log to uranium-bearing ore. However, should geologic mine study of formation porosity and permeability or density show a significant pattern for ore deposition, the more sophisticated logging techniques should be considered.

The author acknowledges the cooperation of D. P. Hearn and the constructive review by R. A. Broding. Appreciation is expressed to Kermac Nuclear Fuels, Phillips Petroleum Company, and the U.S. Atomic Energy Commission, Grand Junction, Colorado, for the use of material presented in this paper.

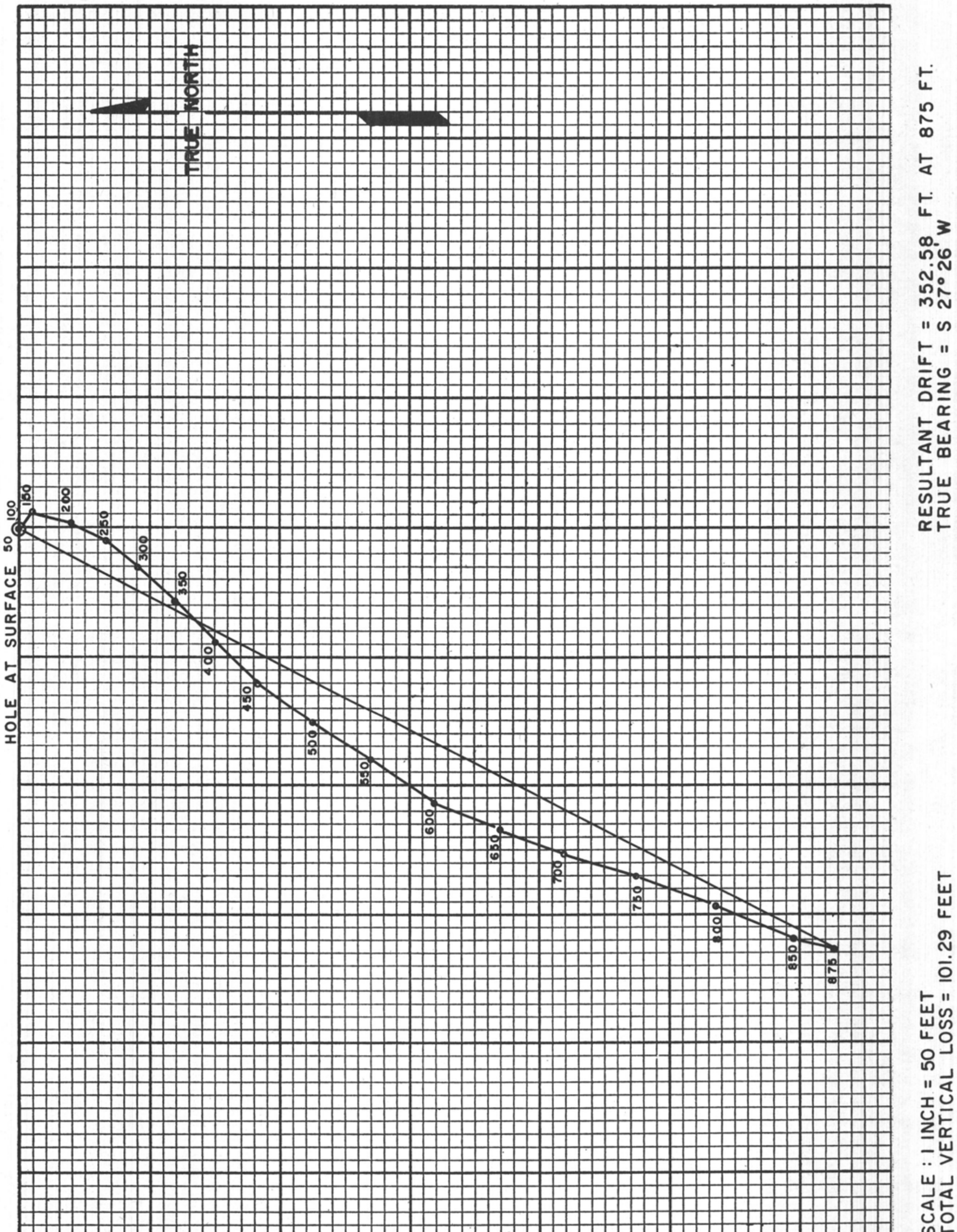


Figure 8

Surface hole deviation survey

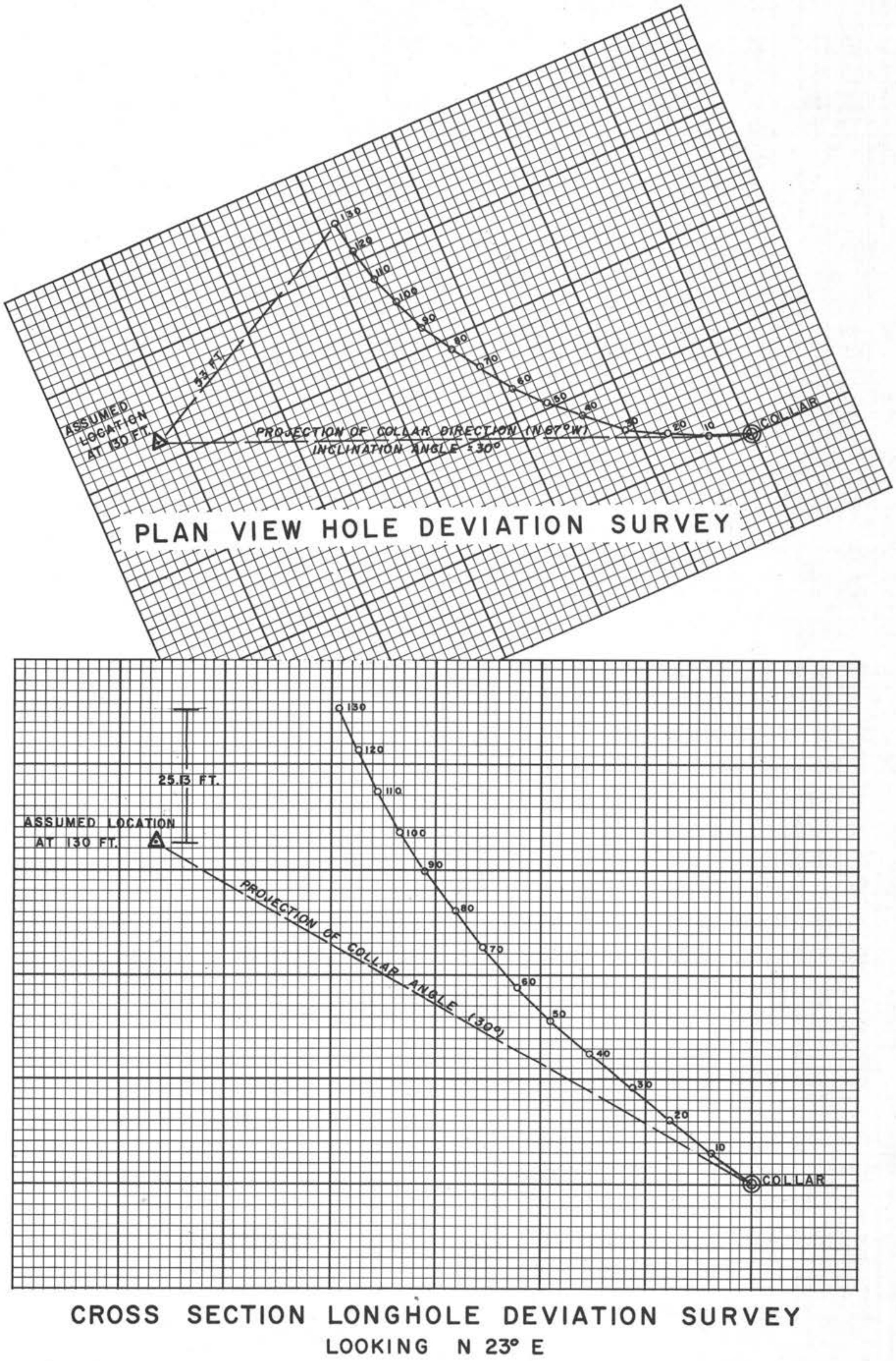


Figure 9

Mine long-hole deviation plot

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# *Estimation of Uranium Ore Reserves by Statistical Methods and A Digital Computer*

W. D. GRUNDY AND ROBERT J. MEEHAN

## ABSTRACT

Uranium deposits display a positively skewed unimodal frequency distribution of assay values, and the statistical methods developed for the South African gold fields can be used for reliable estimation of uranium reserves. Digital computers afford an economical, efficient, and rapid method to handle large amounts of gamma-log sample data and to do the tedious, complex statistical calculations.

## INTRODUCTION

Studies of extensive gamma-ray log sampling data of drill holes in sandstone-type uranium deposits in the Western United States indicate that the assay values are positively skewed. When the sample grades from such an ore deposit are plotted in histogram form (fig. 1), the peak frequency (mode) is near the origin of the plot, and there is a long-drawnout tail extending to the high-grade side of the scale. Such positive skewness of assay values (asymmetry to the right) is a feature found in many other types of metallic ore deposits and has been extensively discussed by De Wijs (1951, 1953), Sichel (1952), Krige (1952), Becker and Hazen (1961), and many other writers.

A theoretical mathematical model, the lognormal frequency distribution in statistical nomenclature, appears to describe adequately the shape of uranium assay value frequencies. This distribution, defined later in this paper, can be used to overcome some of the difficulties encountered in evaluating uranium ore reserves by conventional methods such as polygonal, triangular, cross-sectional, or general outline. This paper describes the use of this statistical model in uranium ore reserve estimation and the use of a high-speed digital computer in the tedious and complex process of gamma-ray log data reduction and statistical calculations.

The practical use and much of the mathematical theory for the lognormal model have been developed by Sichel and by Krige (1952) for the gold fields of South Africa.

## ADVANTAGES OF STATISTICAL MODEL

Conventional methods of ore reserve evaluation ignore the actual distribution of assay values in estimating the average grade (arithmetic mean) of an ore deposit. The average grade of the deposit is simply equated to the arithmetic mean of the sample grades. If the assay values show strong positive skewness, such as uranium values do, mathematical theory can show that the arithmetic mean of the sample grades would not necessarily be the best possible estimate of the true average grade of the ore body, unless the entire deposit were removed by sampling. It can be readily shown that the arithmetic mean of uranium sample grades has a one-sided sensitivity to high-grade values (addition or subtraction of one high-grade value in a set of sample data will affect the arithmetic mean more than the addition or subtraction of one low-grade value). This one-sided sensitivity is widely recognized by mine evaluators; hence, the common practice of arbitrarily reducing high-grade assay values to some lower value in an attempt to arrive at a "safe" estimate of the average grade of the ore deposit. This practice is not recommended because of the risk of underevaluating the deposit.

The statistical estimator of true average grade developed by Sichel (p. 267) is not based on the arithmetic mean of the sample grades. Sichel eliminates the one-sided sensitivity to high-grade values by making use of the geometric mean of the sample grades, a statistic which is relatively insensitive to extreme values. The geometric mean, however, is a negatively biased estimator of the true average grade of the ore body; that is, in the long run, it will underestimate the true value. Sichel overcomes this negative bias by multiplying the geometric mean by a factor based on the variance (a measure of variability) of the logarithms of the sample grades and the number of samples. If the assay values conform to the lognormal frequency distribution, Sichel's estimator in theory and in practice will generally be closer to the true average grade of the ore body than any other estimator.

Conventional methods of ore reserve estimation involve difficulties in estimating reserve parameters when mining cut-off grades are changed. The reason for this is apparent when sample data are arranged in histogram form. Unless the number of measurements is very large, the histogram, while still exhibiting strong positive skewness, is fairly irregular. Because of chance causes, certain assay values may be missed in the sampling program, whereas others may have unusually high frequencies. Such a histogram is said to be "lumpy." Unless the histogram is smooth, estimates of tonnage and grade at various cut-offs will also be "lumpy." If the assay values are lognormally distributed, it is a fairly simple analytic procedure to smooth out the sample frequency data, and in the majority of cases, estimates of tonnage and grade at various grade cutoffs will be moved closer to the true values.

Use of the lognormal distribution allows calculation of close approximations to upper and lower limits of error (confidence limits) of tonnage and grade at various cut-offs. Equally reliable confidence limits of tonnage and grade cannot be obtained if the shape of the distribution is ignored.

## DATA REQUIREMENTS

Several requirements are necessary for valid statistical analysis of sample data, as outlined in this paper.

One requirement is that the sample frequency distribution conform to the lognormal distribution. Sample data should be tested for lognormality by the chi-square test described in standard statistical texts.

Not all positively skewed frequency distributions are log-

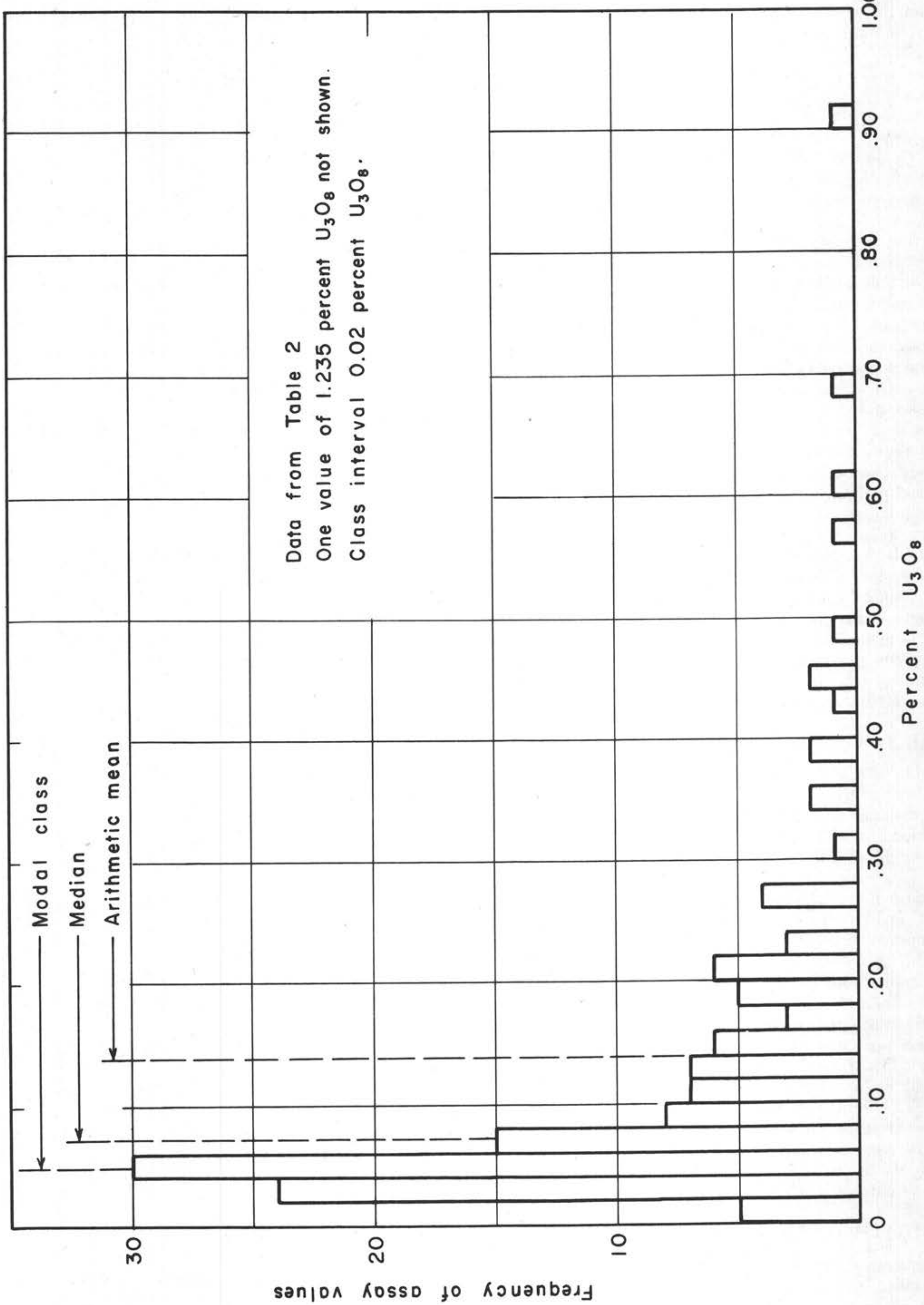


Figure 1

Histogram of assay values from an Ambrosia Lake ore deposit normal, but Krige (196o) describes a method of handling some of these other distributions so that lognormal theory can be used.

Lognormality can be lost in certain cases by including samples from a large, high-grade zone with samples from a separate large low-grade zone and treating the combination as one population. This practice may yield or approach a bimodal distribution. However, treating each zone as one population (stratified sampling) usually restores lognormality.

Random sampling, in which each part of the ore deposit is as likely to be included as any other, is another requirement to satisfy the probability upon which statistical analysis is based. The common practice of sampling by systematic patterns of drill holes might seem to preclude obtaining a random sample of an ore deposit. However, the assay values obtained from systematic sampling generally behave as if they were selected randomly, unless the sample spacing happens to coincide with a spacing of high-grade or low-grade values in the deposit. Objective tests for randomness are outlined by Hazen (1961, p. E13-E24).

The variability of assay values is related to the volume of rock taken for each assay. The larger the volume sampled, the less will be the variability of the sample results. Consequently, for statistical analysis, samples must be of uniform volume.

As presently practiced, uranium ore reserve estimation using gamma-ray logs is based on the assumption of radiometric equilibrium between uranium and its daughter products. The ratio $cU_3O_8$ : eU3O8, however, probably changes with grade. There is empirical evidence that high-grade chemical assays are likely to exceed the corresponding radiometric assays, whereas low-grade chemical assays are likely to be less than the radiometric assays. This relationship has not been thoroughly studied, so an unknown amount of error may be introduced into the statistical analysis.

## THE LOGNORMAL DISTRIBUTION

A variable such as the value of assays representing an ore deposit is said to have a lognormal distribution if the logarithms of the variable conform to the bell-shaped frequency curve defined by the "normal" law of probability.

The assay data of Figure 1, taken from an ore body in the Ambrosia Lake district, expressed in percent $U_3O_8$, are positively skewed. If the natural logarithms of these assay values are plotted in histogram form (fig. 2), their frequencies approach a normal curve. The chi-square test of goodness of fit between the natural logarithms of the assays and the normal distribution shows no reason to doubt the normality of the logarithms. The assay values are therefore considered to be lognormally distributed and hence the superior techniques of ore reserve estimation used by Sichel and by Krige (1952) are applicable to this deposit.

It should be noted that logarithms are to the base e (2.71828 . . .). This is for reasons of mathematical convenience and conforms to orthodox statistical usage.

Below are given certain of the mathematical formulas applicable to the lognormal distribution which are used in estimation of tonnage, grade, and confidence limits.

## MATHEMATICAL FORMULAS

The frequency curve of a lognormal distribution is completely specified by the arithmetic mean and variance of the logarithms of the totality of the items (all the possible assay values) making up the population (uranium deposit). The arithmetic mean of the logarithms is simply their sum divided by their number. The variance of the logarithms is the mean of the squares of the deviations of the logarithms from their arithmetic mean. If z is taken to represent the assay values, and x the natural logarithms of the assay values, the relative frequency curve of x is given by

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-(x-\mu)^2 / 2\sigma^2\right] \quad (1)$$

where

$\mu$ = arithmetic mean of all values of x (the true mean of the population logarithms)

$\sigma^2$ = variance of x

$\sigma$ = standard deviation of x (the square root of the variance)

$\pi$ = 3.14159 . . .

exp = e to the power . . .

The arithmetic mean of z (the average grade of all assay values in the population) is denoted by $\theta$, and

$$\theta = \exp\left(\mu + \frac{\sigma^2}{2}\right) \quad (2)$$

The geometric mean of all assay values

$$= \exp\ (\mu) \quad (3)$$

The frequency of assay values above a selected cut-off value designated $z_i$ (fraction of total tons in ore body above cut-off grade)

$$= \int_{w_i}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\ (-w^2/2)\ dw \quad (4)$$

where the lower limit of the integral, $w_i$

$$= \frac{1}{\sigma}\ (\log_e Z_i - \mu) \quad (5)$$

Substituting the expression for $\mu$ from formula (2), formula (5) can be written as

$$w_i = \frac{1}{\sigma}\left[\log_e Z_i - (\log_e \theta - \sigma^2/2)\right] \quad (5a)$$

The values of the integral in formula (4) can be obtained from tables of the normal probability integral found in standard statistical text books.

The average value of all assay values above cut-off value $z_i$ (average grade of tonnage above cut-off grade $z_i$)

$$= \theta\ \frac{\int_{w_i-\sigma}^{\infty} \exp\ (-w^2/2)\ dw}{\int_{w_i}^{\infty} \exp\ (-w^2/2)\ dw} \quad (6)$$

1. Adapted from Krige (1952, p. 56) and Sichel (*in* Krige, 1952, p. 65).

$$= \theta \frac{\text{frequency for normal integral above } (w_i - \sigma)}{\text{frequency for normal integral above } (w_i)} \quad (6a)$$

*Estimation of required population values*

In practice, the required population values of $\theta$, $\mu$ and $\sigma^2$ will not be known and will have to be estimated from sample data of n assay values.

Sichel's unbiased estimator of $\theta$, the true average grade of the ore deposit, is denoted by t, and

$$t = \exp \bar{x} \left[1 + \tfrac{1}{2}V + \frac{(n-1)}{2^2 \cdot 2!\,(n+1)} V^2 + \frac{(n-1)^2}{2^3 \cdot 3!\,(n+1)\,(n+3)} V^3 + \cdots\right] \quad (7)$$

where

$\bar{x}$ (arithmetic mean of logarithms of sample values)

$$= \frac{1}{n} \sum_{i=1}^{n} x_i \quad (8)$$

V (variance of logarithms of sample values)

$$= \frac{1}{n} \sum_{i=1}^{n} x_i^2 - \bar{x}^2 \quad (9)$$

Formula (7) can be solved by using table values corresponding to V and n as given by Krige (1961, p. 551).

The estimator for population value $\mu$

$$= \bar{x} \quad (10)$$

The estimator for population value $\sigma^2$, is denoted by $s^2$, and

$$s^2 = \left(\frac{n}{n-1}\right) V \quad (11)$$

The estimator for population value $\sigma$, is denoted by s, and

$$s = \sqrt{s^2} \quad (12)$$

*Approximate confidence limits of t-estimator*

Using a table value of the normal probability integral, approximate (not statistically exact) upper and lower five percent limits of error of the t-estimator are given by

upper five per cent limit

$$= t_{.95} = \frac{t}{t'} \exp\,(y + 1.645\ S\ D_y) \quad (13)$$

lower five percent limit

$$= t_{.05} = \frac{t}{t'} \exp\,(y - 1.645\ S\ D_y) \quad (14)$$

where

$$y = \bar{x} + V / 2 \quad (15)$$

$$t' = \exp\,(y) \quad (16)$$

$$S\ D_y \doteq s \sqrt{\frac{1}{n}\left[1 + \frac{n-1}{2n} s^2\right]} \quad (17)$$

## ESTIMATION OF TONNAGES AND AVERAGE GRADES AT VARIOUS CUT-OFFS AND CONFIDENCE LIMITS

Estimates of the most likely tonnage at a given cut-off grade may be obtained by appropriate substitutions of s, $s^2$, and t, for 0-, $a^2$ and 0 in formlas (5a) and (4), and multiplying (4) by the tonnage of rock considered to be sampled. The most likely average grade at a given cut-off is obtained from formula (6a).

The total tonnage of rock sampled is derived from

$$\text{total tonnage} = \frac{\text{area x average thickness}}{\text{tonnage factor}}$$

where

area = square feet of area within which mineralized drill holes occur

average thickness = average thickness of mineralized rock per drill hole obtained by dividing the total footage sampled by the number of drill holes

tonnage factor = cubic feet per ton

Estimates of tonnage and grade at the upper and lower five percent levels of confidence at a given cut-off are obtained by substitution of $t_{.95}$ and $t_{.05}$ for *0* in (5a), (4), and (6a).

The validity of substituting s and $5^2$ from (12) and (11 ) for *0*- and $0\text{-}^2$ in (5a), (4), and (6a) is at present uncertain. The estimators s and $s^2$ are derived from gamma-ray logging data. A gamma-ray log samples a cylinder of rock roughly two feet in diameter, representing a volume considerably less than the volume of a mining unit or ore reserve block. The variance of ore reserve block grades could be less than that of gamma-log grades because variance tends to decrease with increasing volume of the sample.

If the variance of drill hole data greatly exceeds that of mining units, the effect will be to underestimate tonnage and overestimate grade at low cut-off grades and to overestimate tonnage and grade at high cut-off grades. This would be true of any method of ore estimation.

Table I and Figure 3 show the relationship between logarithmic variance, tonnage, average grade, and fraction of total pounds $U_3 0_8$ for an ore body whose mean grade at a o.00 percent $U_3 0_8$ cutt-off is o. o percent $U_3 0_8$. Assume the logarithmic variance of the drill hole gamma-ray log data to be .o, but the logarithmic variance of mining-sized units to be 0.5. It is evident that serious errors arise in evaluating this particular ore body on the basis of sample variance.

Krige (1952, p. 58-61) outlines procedures for estimating the variance of ore reserve blocks. These procedures have not yet been attempted, and until the actual variance of ore reserve blocks can be established, the variance established from drill hole values is used as a first approximation for estimating ore reserves at different cut-offs.

## COMPUTER PROGRAMS

The arithmetic operations involved in gamma-ray log interpretation and the computation of logarithmic statistical values for large amounts of sample data are so monotonous and time-consuming as to be impractical to carry out by hand. Use of a digital computer produces results rapidly and eliminates chances of human arithmetic errors. Following is a brief general discussion of the AEC-developed computer programs

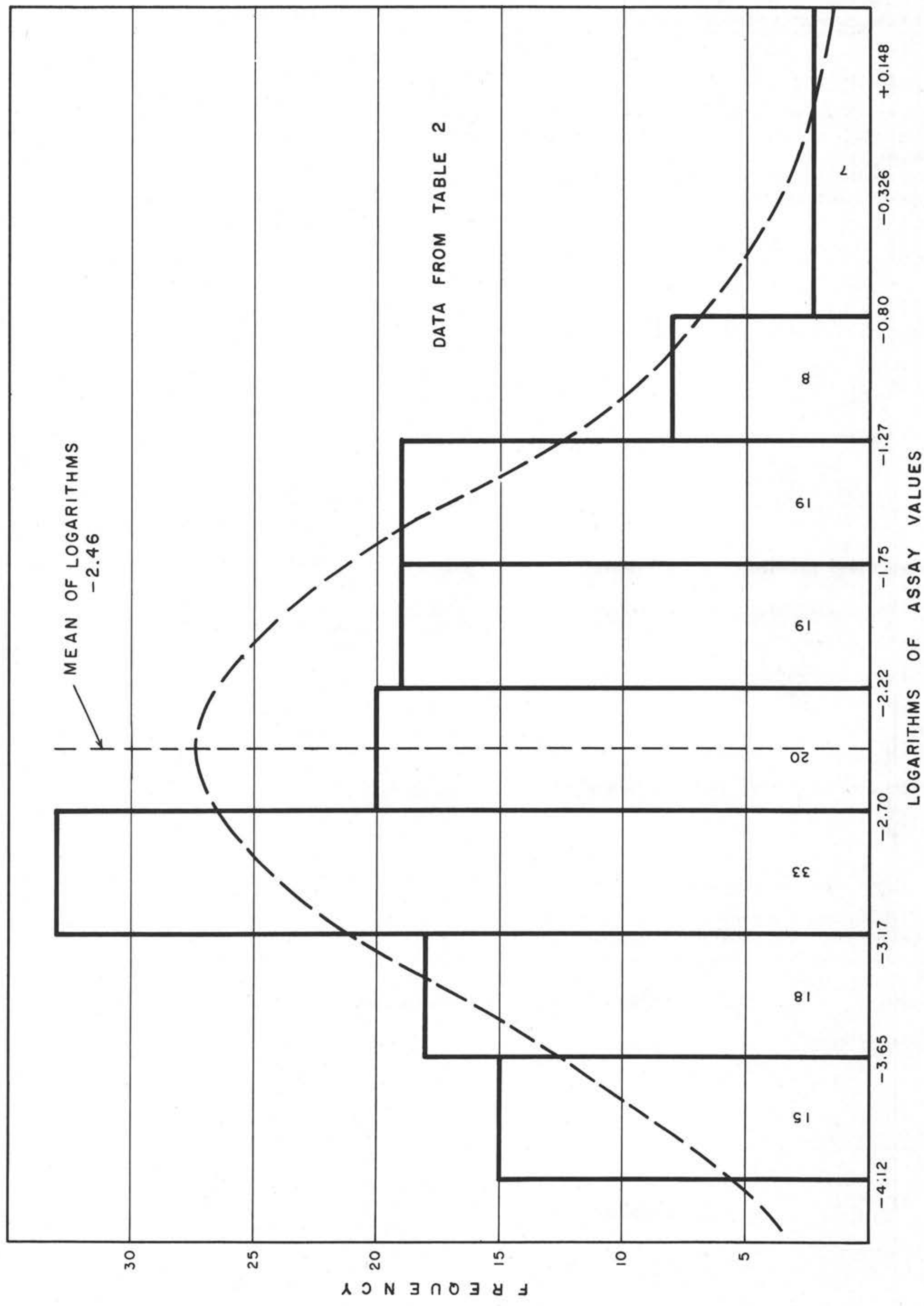


Figure 2

HISTOGRAM OF NATURAL LOGARITHMS OF ASSAY VALUES FROM AN AMBROSIA LAKE ORE DEPOSIT. (DASHED LINE FITTED NORMAL CURVE)

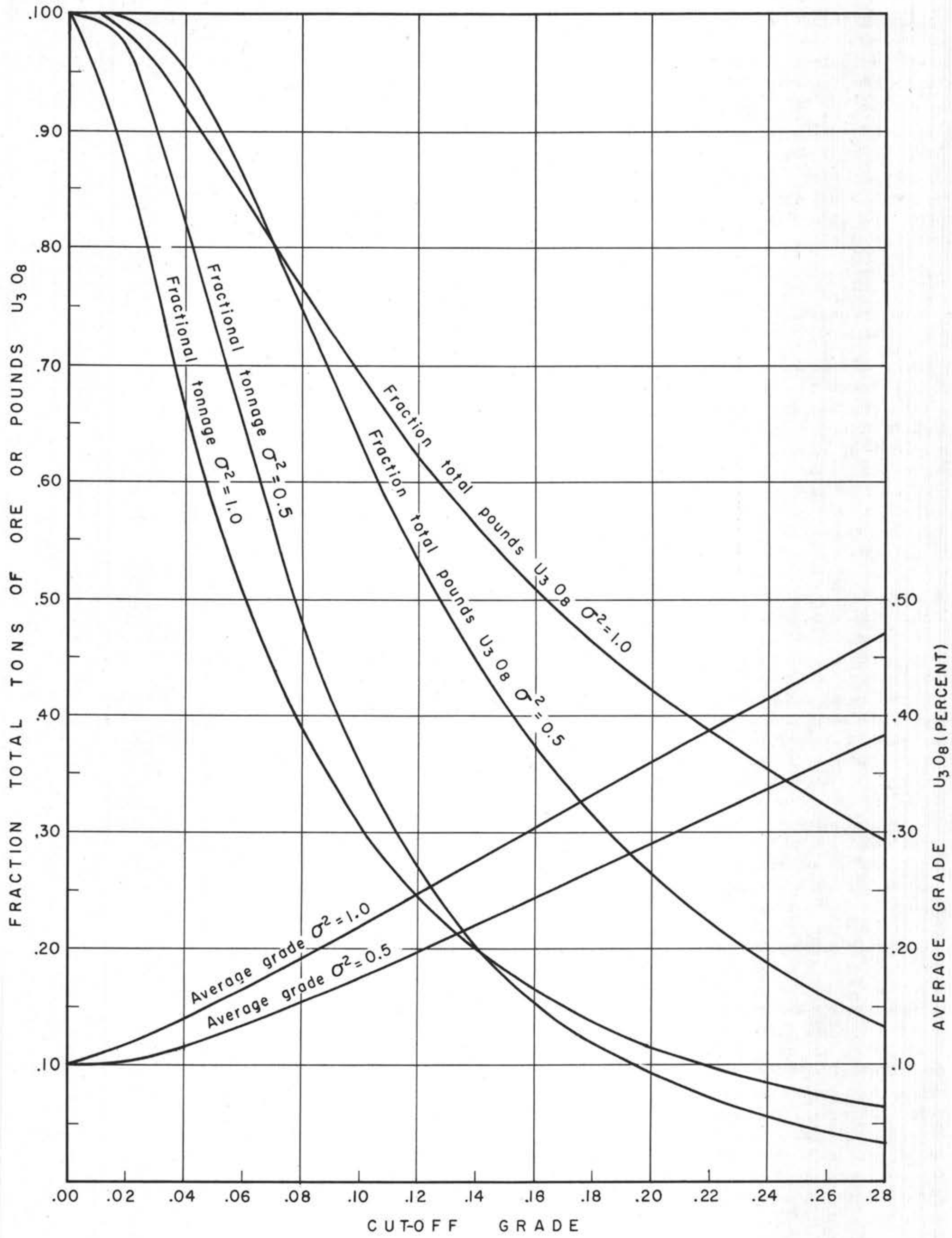


Figure 3

RELATIONSHIP OF TONNAGE, AVERAGE GRADE, AND POUNDS $U_3O_8$ WITH LOGARITHM VARIANCE ($\sigma^2$)

which are written in FORTRAN language for the IBM 7090 computer at Sandia Corporation, and their software (subprograms, subroutines, function subroutines, and general program routines).

## STATISTICAL

ORSAC (Ore Reserve Statistical Analysis Calculation, fig. 4) is a computer program designed to compute various statistical estimators from gamma-ray logging data. Computer time to generate results is about 5o gamma-ray logs a minute. The input in the form of IBM cards for this program consists of the following:

I. Table—normal probability integral
2. Property identification
3. Minimum thickness
4. Gamma-ray log data

Each mineralized zone has a set of data cards headed by a control card which has necessary information such as ore block number, hole number, hole coordinates, hole collar elevation, depth to uppermost log reading, equipment calibration constant, resolving time, drill-hole media (mud, water, air) factor, logging scale (counts per second), reading interval (either one half or one foot), deflection type (inches, cps uncorrected for resolving time or cps corrected for resolving time). The deflection readings are punched on cards which follow the header card.

The first step in the ORSAC program is the interpretation of gamma-ray logs into one-half or one-foot assay values by the GAMLOG subroutine. An array is then generated by determining the average grades of consecutively combined assay values into averages for a minimum thickness corresponding to a minimum underground mining height. The arithmetic mean, variance, standard deviation, skewness, kurtosis (peakedness), and the twentieth, fiftieth, and eightieth percentiles of the array are then computed. The total footage sampled, number of drill holes, and average thickness per drill hole are also determined.

SICHEL subroutine then computes natural logarithmic values of the elements in the array and computes the geometric mean, logarithmic variance, logarithmic standard deviation, and the t-estimator; that is, formula (7).

NORCHI subroutine computes the chi-square test of goodness of fit of the natural logarithmic values of a normal distribution.

LOOKUP subroutine computes the fraction of the total tons above cut-offs ranging from 0.01 to 0.30 percent $U_3O_8$ in increments of 0.01 percent $U_3O_8$, the average grade of this tonnage, and the error limits. The values are computed from formulas (4), (6a), ( 3), and (14) above.

The output or print-out lists the property identification, the gamma-ray log interpretations from the GAMLOG subroutine, lognormality chi-square test results, arithmetic statistical estimators, logarithmic statistical estimators, cut-offs, fraction of total tons above cut-off, average grade of tons above cut-off, error limits, the assay values in the minimum thickness array, total number of drill holes, total footage sampled, and average thickness per drill hole.

## GAMMA-RAY LOG INTERPRETATION

The GAMLOG computer subroutine (Scott, 1962) is designed to convert gamma-ray log data into equivalent $U_3O_8$ values by a trial-and-error interpretative process. The objective of the process is to determine a separate grade for each half-foot or one-foot layer of rock represented by a gamma-ray

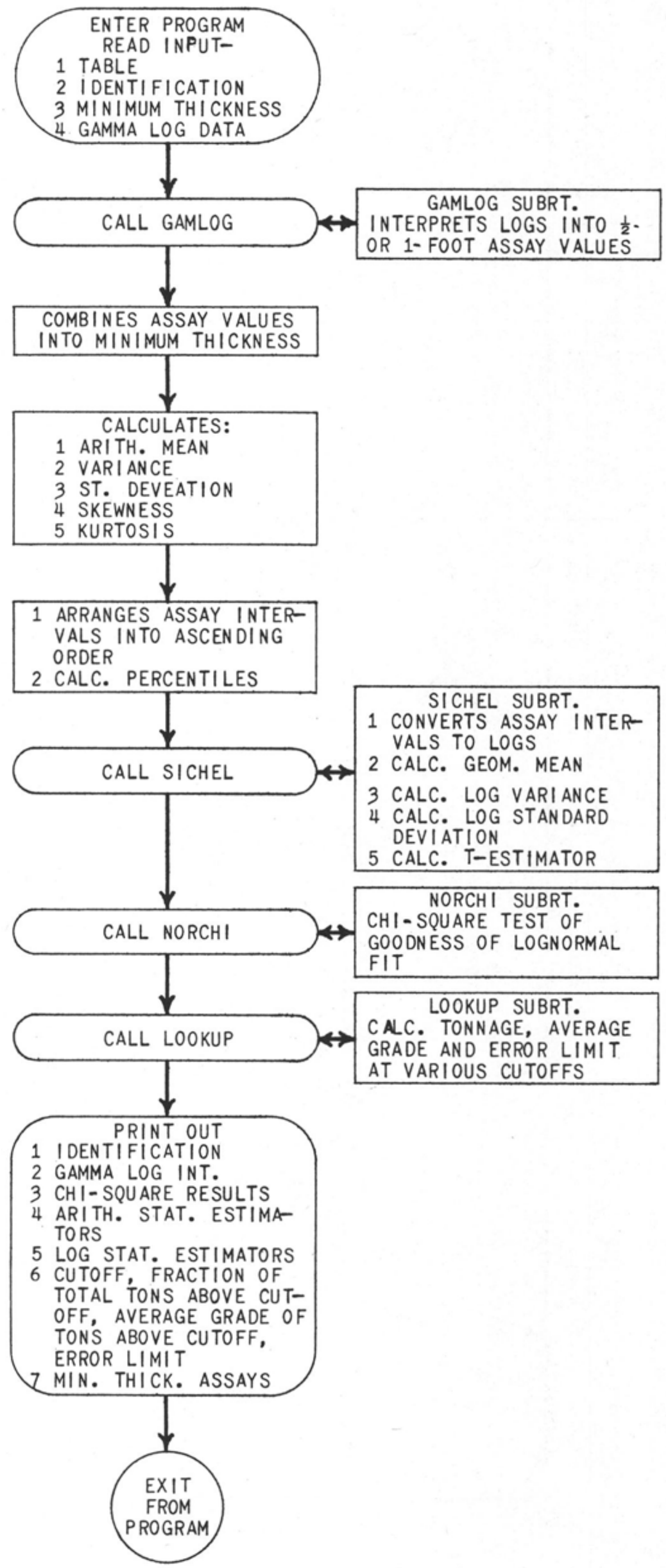


Figure 4

Flow diagram of ORSAC computer program

log deflection reading. The method used by the GAMLOG subroutine would not be practical to carry out by hand because it would be too time-consuming. The computer time to generate results from input data is short, about one minute for i oo average logs.

## EXAMPLE OF RESULTS

Table 2 is an example of the data and results of the analysis of one ore block in the Ambrosia Lake area. A comparison of actual production with ( ) the results from the statistical method of ore reserve estimation of this ore block and (2) those calculated by a conventional method, using the mining cut-off of six feet at 0.15 percent $U_3O_8$, is as follows:

| | *Production plus blocked out reserves* | *Statistical method* | *Conventional method* |
|---|---|---|---|
| Tons | 208,300 | 200,400 | 195,000 |
| Average grade (percent $U_3O_8$) | 0.298 | 0.31 | 0.34 |
| Pounds $U_3O_8$ | 1,242,000 | 1,242,500 | 1,326,000 |
| Percentage of production (lbs. $U_3O_8$) | 100 | 100 | 107 |

## ECONOMIC CONSIDERATIONS

The statistical estimators of tonnage, average grade, and confidence limits provide a sound and flexible basis for the evaluation of the economic risk in developing and mining a deposit.

The statistical method, in addition to giving the theoretically best estimate of the average grade, provides good approximations of upper and lower confidence limits. Since the average grade and tonnage estimated from a sample of n observations will probably differ from the true grade and tonnage of the deposit, the confidence limits of the estimation is the range within which it can be said the true average grade and tonnage lies with a designated degree of confidence. At a 9o-percent level, the true average grade and tonnage should be within the confidence limit 90 times out of loo. Confidence limits calculated by methods ignoring lognormality would require a larger number of samples to yield an estimate of equivalent reliability. The lower limit graphically demonstrates the risk inherent in the decision to mine the deposit. If the minimum tonnage and average grade for an economical mining operation is at the lower five percent confidence limit, a decision to mine the deposit would be correct approximately 19 times out of 20.

Confidence limits other than 90 percent, as used in this paper, can be selected according to personal preference.

## CONCLUSIONS

The advantages of the statistical-computer method of uranium ore reserve estimation are as follows:

1. The tonnage and average grade obtained by statistical methods are generally closer to the true values than those obtained by conventional methods.
2. The statistical method gives tonnages, average grades, and error limits at different cut-off grades.
3. Upper and lower error limits of ore reserve tonnage and average grade, and the measure of variability, provide a sound and flexible basis for decisions as to the economic aspects of a deposit.
4. The digital computer affords an economical, efficient, and rapid method for handling large amounts of data and for tedious, complex statistical calculations. Recalculations are done rapidly when new data are obtained or variables changed. Data cards used for the statistical analysis can be used also for other computer programs.

The main disadvantage of the statistical—computer method is the requirement of access to a digital computer. The computer program and data preparation for computer input require careful and detailed checking to guarantee correct results. However, computer edit programs can be designed to do much of this checking.

TABLE 1. RELATIONSHIP OF TONNAGE, AVERAGE GRADE, AND VARIANCE
(All values given in percent)

| CUT-OFF GRADE | PERCENT OF TONNAGE ABOVE CUT-OFF GRADE | | AVERAGE GRADE OF TONNAGE ABOVE CUT-OFF $U_3O_8$ | | PERCENT OF TOTAL POUNDS $U_3O_8$ | |
|---|---|---|---|---|---|---|
| | DRILL HOLE $\sigma^2 = 1.0$ | MINING $\sigma^2 = .5$ | DRILL HOLE $\sigma^2 = 1.0$ | MINING $\sigma^2 = .5$ | DRILL HOLE $\sigma^2 = 1.0$ | MINING $\sigma^2 = .5$ |
| 0.00 | 100.00 | 100.00 | 0.100 | 0.100 | 100.00 | 100.00 |
| 0.02 | 86.63 | 97.28 | 0.114 | 0.102 | 98.76 | 99.23 |
| 0.04 | 66.13 | 82.69 | 0.139 | 0.115 | 91.92 | 95.09 |
| 0.06 | 50.44 | 64.39 | 0.133 | 0.133 | 84.23 | 85.63 |
| 0.08 | 39.09 | 48.48 | 0.196 | 0.154 | 76.62 | 74.66 |
| 0.10 | 30.85 | 36.17 | 0.224 | 0.176 | 69.10 | 63.66 |
| 0.12 | 24.77 | 27.06 | 0.252 | 0.199 | 62.42 | 53.85 |
| 0.14 | 20.16 | 20.36 | 0.280 | 0.222 | 56.44 | 45.20 |
| 0.16 | 16.60 | 15.44 | 0.308 | 0.245 | 51.13 | 37.83 |
| 0.18 | 13.83 | 11.82 | 0.336 | 0.267 | 46.47 | 31.56 |
| 0.20 | 11.64 | 9.13 | 0.364 | 0.291 | 42.36 | 26.57 |
| 0.22 | 9.89 | 7.09 | 0.391 | 0.315 | 38.67 | 22.33 |
| 0.24 | 8.45 | 5.57 | 0.419 | 0.338 | 35.41 | 18.83 |
| 0.26 | 7.27 | 4.41 | 0.446 | 0.361 | 32.42 | 15.92 |
| 0.28 | 6.30 | 3.51 | 0.473 | 0.385 | 29.80 | 13.51 |
| 0.30 | 5.49 | 2.86 | 0.500 | 0.402 | 27.45 | 11.50 |

Hypothetical case: Values derived using formulas (5a), (4), and (6a).

## TABLE 2. TABULATION OF RESULTS OF STATISTICAL ANALYSIS

*Assay values:* Ascending $U_3O_8$ percent values of assays

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.017 | 0.017 | 0.018 | 0.018 | 0.019 | 0.020 | 0.021 | 0.022 | 0.022 | 0.023 |
| 0.023 | 0.023 | 0.024 | 0.025 | 0.026 | 0.027 | 0.027 | 0.029 | 0.030 | 0.031 |
| 0.031 | 0.032 | 0.033 | 0.034 | 0.034 | 0.034 | 0.035 | 0.036 | 0.036 | 0.041 |
| 0.041 | 0.041 | 0.042 | 0.043 | 0.045 | 0.045 | 0.046 | 0.046 | 0.046 | 0.047 |
| 0.047 | 0.048 | 0.049 | 0.050 | 0.051 | 0.052 | 0.052 | 0.052 | 0.052 | 0.053 |
| 0.054 | 0.054 | 0.054 | 0.054 | 0.055 | 0.055 | 0.058 | 0.059 | 0.059 | 0.060 |
| 0.061 | 0.061 | 0.064 | 0.065 | 0.066 | 0.066 | 0.068 | 0.069 | 0.072 | 0.073 |
| 0.073 | 0.075 | 0.075 | 0.078 | 0.081 | 0.083 | 0.083 | 0.086 | 0.088 | 0.093 |
| 0.093 | 0.093 | 0.101 | 0.103 | 0.105 | 0.106 | 0.114 | 0.115 | 0.116 | 0.123 |
| 0.126 | 0.130 | 0.132 | 0.132 | 0.134 | 0.139 | 0.140 | 0.150 | 0.150 | 0.151 |
| 0.153 | 0.159 | 0.163 | 0.165 | 0.166 | 0.182 | 0.185 | 0.185 | 0.195 | 0.195 |
| 0.201 | 0.203 | 0.209 | 0.214 | 0.218 | 0.219 | 0.221 | 0.224 | 0.230 | 0.267 |
| 0.268 | 0.272 | 0.276 | 0.280 | 0.300 | 0.342 | 0.358 | 0.388 | 0.394 | 0.429 |
| 0.441 | 0.442 | 0.469 | 0.496 | 0.574 | 0.612 | 0.691 | 0.902 | 1.235 | |

Number of drill holes: 30. Total footage of samples: 769.5. Average thickness: 25.65 ft.
Average area per drill hole: 13,000 sq ft.

*Statistical estimators*

**Arithmetic**

| | |
|---|---|
| Mean (percent) | 0.139 $U_3O_8$ |
| Variance | 0.0298 |
| Standard deviation | 0.1727 |
| Standard error of the mean | 0.0146 |
| Skewness | 3.2141 |
| Kurtosis | 16.6730 |
| Median (percent) | 0.073 $U_3O_8$ |
| 20 percentile (percent) | 0.035 $U_3O_8$ |
| 80 percentile (percent) | 0.202 $U_3O_8$ |

**Logarithmic (Base e)**

| | |
|---|---|
| "t" Estimator (percent) | 0.133 $U_3O_8$ |
| Logarithmic mean | −2.4587 |
| Logarithmic variance | 0.9035 |
| Logarithmic standard deviation | 0.9505 |
| 16 percentile (percent) | 0.33 $U_3O_8$ |
| 50 percentile (percent) | 0.086 $U_3O_8$ |
| 84 percentile (percent) | 0.222 $U_3O_8$ |

*Chi-square results*

**Arithmetic**

| Class interval | | Observed frequency | Theoretical frequency |
|---|---|---|---|
| 0.01 | 0.096 | 82 | 55.8 |
| 0.096 | 0.183 | 24 | 27.4 |
| 0.183 | 0.269 | 15 | 24.3 |
| 0.269 | 0.355 | 5 | 16.8 |
| 0.355 | 0.441 | 5 | 9.1 |
| 0.441 | ≠ | 8 | 5.6 |
| | | 139 | 139.0 |

Computed chi-square – 26.4983
Degrees of freedom – 3
Probability – 0.00001

**Logarithmic (Base e)**

| Class interval (logarithms) | | Observed frequency | Theoretical frequency |
|---|---|---|---|
| −4.12213 | −3.64688 | 15 | 14.7 |
| −3.64688 | −3.17163 | 18 | 16.8 |
| −3.17163 | −2.69637 | 33 | 24.3 |
| −2.69637 | −2.22112 | 20 | 27.4 |
| −2.22112 | −1.74587 | 19 | 24.3 |
| −1.74587 | −1.27062 | 19 | 16.8 |
| −1.27062 | −0.79536 | 8 | 9.1 |
| −0.79536 | ≠ | 7 | 5.6 |
| | | 139 | 139.0 |

Computed chi-square – 7.1775
Degrees of freedom – 5
Probability – 0.21

*Computed fractional tonnage, average grade, confidence limits (0.90) for various grade cut-offs*

| | | | Confidence limits (0.90) | | | |
|---|---|---|---|---|---|---|
| | | | Lower 0.05 limit | | Upper 0.95 limit | |
| Cut-off ($U_3O_8$) (%) | Fractional tonnage above cut-off | Average grade of fractional tonnage ($U_3O_8$) (%) | Tonnage fractional | Average grade ($U_3O_8$) (%) | Tonnage fractional | Average grade ($U_3O_8$) (%) |
| 0.05 | 0.715 | 0.175 | 0.654 | 0.159 | 0.768 | 0.194 |
| 0.10 | 0.437 | 0.240 | 0.370 | 0.225 | 0.501 | 0.258 |
| 0.15 | 0.278 | 0.307 | 0.224 | 0.292 | 0.335 | 0.326 |
| 0.20 | 0.186 | 0.374 | 0.144 | 0.359 | 0.233 | 0.393 |
| 0.25 | 0.129 | 0.440 | 0.097 | 0.425 | 0.167 | 0.460 |
| 0.30 | 0.093 | 0.506 | 0.067 | 0.491 | 0.123 | 0.526 |

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# *Uranium Mining in the Grants District*

*I.* M. GAY

## ABSTRACT

Uranium mining in the Bluewater-Ambrosia Lake area, New Mexico, began in 1951 with production of both limestone and sandstone ores. The development of a milling process to treat limestone ores, the establishment of a government buying station, and the construction of five processing plants were accomplished by the end of 1958. Sixty mines were in operation at various times during the period 1952-1962-Thirty-three mines are now active, accounting for more than 4o percent of the total annual domestic production.

Ore is mined from deposits both above and below the water table, but about 90 percent of present production is from wet-ore bodies. Access to ore bodies is principally through vertical shafts, although rim stripping, adits, and inclined shafts are also utilized. Depths of vertical shafts are up to 1400 feet, through which as much as 400,000 tons of ore a year may be hoisted from a single mine.

Underground haulage is chiefly by Diesel-powered trackless equipment in mines above the water table and by rail with conventional mine cars and battery locomotives in mines below the water table. Development in mines above the water table is usually within the ore bed, while wet mines are developed by track haulageways driven below the ore.

Problems encountered during extraction include ground support, ventilation, and excess ground water. Operating costs, safety, and working conditions have been improved by draining the ground water from the ore extraction areas before entry and by utilizing track equipment for main haulageways in mines below the water table.

## INTRODUCTION

Uranium mining in the area began on a modest scale during 1951 with production of both limestone and sandstone ores. The nearest market then was at Monticello, Utah. Mining expanded rapidly following the development of a new milling process for treating the limestone ores and the construction of a processing mill and buying station near Blue-water in 1953. The discovery of the major Morrison sandstone deposits in the Ambrosia Lake region during 1955-1957 was followed by the erection of four much larger treatment plants in 1958. Mill feed requirements of these plants resulted in a major increase in mine production. Thus, in a decade the Grants district expanded from rim outcrop operations producing a few thousands of tons annually to a major underground mining district producing 3 million tons annually.

During the decade 1952-1962, 6o mines operated at various times in or near T. 12, 13, 14 N., R. 9 and 10 W. Thirty-three mines were active as of January 1, 1963, thirteen of which produce 90 percent of the total ore tons mined a year. Many of the smaller and intermediate size deposits have now been exhausted, and several larger mines are rapidly depleting their reserves.

Individual mines differ greatly in size and economic significance. The smaller properties, each operating with a minimum capital investment, may produce only a few hundred tons of ore a year. The operation may be limited to a segment of one mining claim, with production coming from scattered pits. The large underground mines, on the other hand, may require a capital investment of several millions of dollars a mine, with individual production figures of 200,000 to 400,000 tons a year. Two or more sections of land may be mined through a single shaft ranging from 800 to more than 1400 feet in depth.

## OPEN-PIT MINING

Conventional open-pit mining has provided the major part of the Todilto Limestone ore produced to date, small tonnage from one open pit in the Dakota Formation and a substantial tonnage of ore from the Morrison sandstone outcrops near Poison Canyon. Open-pit operations in this area have been confined to deposits lying 6o feet or less below the ground surface; thus, annual production has declined rapidly as the shallow deposits became exhausted.

## UNDERGROUND MINES ABOVE THE WATER TABLE

*Environment.* Ore bodies above the water table occur in both limestone and sandstone host rocks. Because of variations in the regional dip of the host rocks as well as in topography, the water table occurs at different depths throughout the district. Ground water may be as shallow as 8o feet below the surface near the outcrop to more than 500 feet in depth in the main Ambrosia Lake area. All open-pit mines, most of the shallow mines, and a few deep (± 500 feet) mines have produced from above the water table.

*Modes of entry.* A variety of entry methods is used for access to dry-ore bodies. Deposits near the outcrop are entered by either adits or the side slopes of open pits. The shallow deposits are reached by shafts inclined from 5 to 45 degrees. Ore bodies from 100 to more than 500 feet in depth are commonly developed through vertical shafts, such as conventional rectangular shafts having one and one-half to three compartments, elliptical shafts measuring 4 x 8 feet, and circular shafts up to 12 feet in diameter. Supporting material may be wood, steel, or concrete lining.

*Development.* Early development was by use of conventional tracked haulageways on or beneath the ore level. Rapid changes in ore elevation due to ore-body stratigraphic changes and to variations of the regional dip (3 tor 5 degrees) required the removal of excessive waste rock and the installation of many internal inclines. As a result, haulage costs were greatly increased.

Diesel-powered trackless equipment has been almost universally adopted in the district for loading and tramming in mines above the water table. This type of equipment, modifled from larger earth-moving machines, was adapted to underground usage upon governmental approval and can be used readily on grades of ten percent. It can transport rock economically in excess of one mile when provided with good roadbeds, which are maintained without difficulty in a dry mine. Calcium chloride (sometimes combined with jet water sprays) is used extensively on long haulageways to avoid dust and to aid in roadway maintenance.

Loading may be by hand shovel, slusher ramp, or by air, electric, or Diesel-powered crawler loaders which are sometimes operated from remote control panels. The trackless haulage equipment used varies from one-ton battery-powered scootcretes through many sizes to large eight-ton Diesel-powered trucks.

The jackleg-type air drill is universally used for drilling blast rounds. Ammonium nitrate fuel oil has recently been replacing conventional dynamite for blasting.

Present development, which represents almost complete extraction in parts of the small deposits, is usually within the ore layers parallel to the long axis and extending to the limits of either the deposit or the mining property. Headings are then developed to the limits of the deposit across the long axis at variable (50- to 100-foot) intervals. Underground long-hole drilling, used to help define the ore body and for ore-reserve work, usually accompanies the development work. It is normally completed before stoping or retreat mining starts.

*Stoping.* The pillars of ore left after developing a large ore body ordinarily comprise 3o to 70 percent of the original deposit. They are usually extracted by open stoping, normally by retreating from the extremities of an ore body or property line. A few concrete pillars have been placed to aid in solving some difficult ground-support problems, and in one mine, square-set timbering is used for portions of the deposit. The common practice is to install roof bolts and/or stulls for safety. Open-timber-cribbing support is also widely used.

Broken ore is recovered from open stopes by slushers or various types of crawler loaders which are sometimes operated by remote control panels to avoid exposing employees to particularly dangerous conditions. The stoped area seldom caves completely (back or roof collapse) when mining the smaller and narrower deposits (± 100 feet across long axis). Final extraction of the large, thick, ore deposits by open stoping always results in collapse of the overlying material. Usually caving occurs naturally along a line or front which follows the retreat stoping but is sometimes induced by blasting the back to lessen the load on the remaining extraction area. Collapse areas have extended to the surface from depths in excess of 400 feet. An accompanying article on the Marquez mine reports on some of the difficulties resulting from this type of caving problem. Very little mine filling for ground control has been used in the dry mines to date.

*Ventilation.* Both dry and wet mines require the positive (mechanically induced) flow of fresh air to working areas for the removal of radon, Diesel, blasting, and other gases. Radon is the main problem, as the State mining laws are quite stringent concerning the permissible concentrations of this odorless, colorless, and tasteless gas. Therefore, a large flow of fresh air through the working areas of even a small mine is a necessity.

Inlet or outlet air passageways from the surface are established by drillholes of 18 to 84 inches in diameter that may be drilled by churn or rotary equipment. In the shallow mines, larger holes may be equipped with ladders attached to the steel casing for emergency exits, while in the deeper mines, they are equipped with a torpedo cage and hoist. Ventilation is a constantly changing problem as the mine workings either expand or decrease in size and may be further complicated by multilevel ore zones in parts of the property. Several of the mines have driven raises to the surface especially for ventilation. These have a much greater cross section than the drilled holes, thus permitting a larger flow of air with equivalent electric power.

## UNDERGROUND MINES BELOW THE WATER TABLE

*Environment.* Wet ores have been encountered in both limestone and sandstone mines at depths ranging from 8o to more than 500 feet below the shaft collars. Historically, there has been a greater number of mines in dry-ore bodies, although the greatest tonnage produced to date has come from deposits lying below the water table. Currently, about 90 percent of the Grants district production is extracted from deposits which are, or were until drained, below the ground-water table.

Pumping rates during the development of the different mines ranges from 25 to more than 2000 gallons a minute. Ground-water flowage gradually declines in most mines to less than one third of the maximum amount as development nears completion. The deeper mines ( 1000 feet) encounter a heavy flow of ground water under ± 25o pounds hydraulic head when piercing the Dakota Formation by shaft sinking. The water in the Dakota is sealed from the ore zones by the intervening Brushy Basin mudstone. Several methods of placing various kinds of grouting into the sides of the shafts to "seal off" the Dakota water flow have been only partially successful. The more successful mines have removed most of the ground water from the ore-extraction zones by various drainage methods before attempting to mine the deposits.

*Modes of entry.* Access is provided by shafts, chiefly vertical, with a few inclined at from a o-percent slope to a 3o-degree angle (about 58 percent). The location may be determined by topography, either surface or underground, or the approximate center of the tonnage expected to be extracted. Shaft walls are supported by wood, steel, concrete, or combinations of all three materials. Shaft sinking costs less than $150 to several hundred dollars a foot of depth. The time and cost necessary to sink a shaft vary with the desired depth, type of ground, and the amount of ground water encountered, with the accompanying delays required for grouting efforts.

The vertical shafts are chiefly rectangular in design and range from 5 x 9 to 8 x 17 feet inside ground support. They may be divided into from two to five compartments. One 33-inch diameter, steel-cased churn drillhole 370 feet in depth has been used as a production shaft for a small mine. A somewhat larger deposit was extracted through a 7-foot-diameter shaft 460 feet in depth using 18-inch steel culvert segments as wall plates that were anchored by concrete at 7-foot centers. The concrete-lined shafts have avoided most of the maintenance costs and delays in production experienced in mines having shafts lined with other types of ground support.

*Development.* The shaft station or stations from which track haulageways are advanced usually are designed to permit excavation in the most competent of the available sedimentary beds that will permit access at a practical gradient to the desired ore bodies.

Most of the wet mines originally started haulageways in ore horizons using trackless equipment. Rapid changes in ore elevations soon created serious drainage problems and extremely poor roadbeds in the comparatively soft sandstone and shale. High maintenance costs resulted and the trackless machines were in operation less than 5o percent of the working period. This extraction technique proved to be very expensive and all but one of the operating mines in wet sandstone ores have changed to track haulage with primary development beneath the ore zones. Haulageways are not driven in the Morrison shale, if practical to avoid, as they usually require expensive timbering with excessive maintenance of both timber and roadbed. The haulageways are designed to traverse beneath the probable long axis of the target ore body which must then be defined by long-hole drilling. This drilling also drains most of the ground water from the ore zones. Ore-body drainage of a limited volume designed for extraction may be very rapid, a matter of a few weeks, or it may require several months, depending on the thickness and character of the surrounding sandstone and shale.

Raises, single or double compartment, are driven to the ore zone or zones at 50- to 200-foot intervals along the haulageway. Stope development drifts connect the raises to establish ventilation courses. Development then proceeds as described under dry *mines,* except that loading is chiefly by use of slushers. A few mines have drained the ore zones sufficiently to permit the efficient use of trackless loaders for development in the ore bodies.

Many months of development work were required in most of the large mines before the deposits were drained and orebody outlines determined sufficiently to achieve the desired production rates.

*Stoping.* Final extraction or stoping of the ore outlined by development and long-hole drilling is performed chiefly with little ground support or use of filling by open-stoping techniques, as described under dry *mines.* The broken ore is moved chiefly by use of Blusher equipment into the raise chutes and then trammed to the shaft by conventional mine cars and battery locomotives.

The thicker (3o to plus loo feet) stope areas have in general been mined by establishing a slot across the deposit and longhole blasting of the adjacent ore into the slot area. This method has given satisfactory results when the areal extent is comparatively small or when one horizontal dimension of the thick ore is not excessive. Removal of large areas of thick ore by this method results in subsidence of the overlying material with excessive dilution of the broken ore and creates additional problems for mining the remaining portion of the deposit. A part of one thick deposit was extracted by cut-and-fill mining, using a front-end loader for removing broken ore and placing dry filling introduced into the mine through an old ventilation drillhole.

Use of filling as an aid in ground control is gradually increasing in the Ambrosia Lake mines, some of which introduce dry material into or near the desired fill area through 15-inch drillholes from the surface. Most of the filling material is the desired fraction obtained by classification of sand dunes or mill tailings, which are introduced into the mine workings as a slurry. The filling is used to stabilize caved areas, stop caving of open-stoped cavities, or as a routine part of the extraction process. The mines routinely using filling for all stoping are the deepest in the area having shafts that encountered a heavy flow of water when sinking through the Dakota sandstone. The Dakota Formation overlies the stoping area from 10o to 200 feet in vertical distance. Mine filling is used to prevent subsidence which would rupture this aquifer and flood the mine workings. Additional benefits obtained, compared to open stoping, include much easier control of ventilation, better recovery of ore, and less difficulty with ground support in adjacent stopes and haulageways.

In one of these mines, thick ore is extracted by use of square-set timbering with subsequent filling; in another, the lower ore is mined to a convenient height and areal extent by using stulls and some roof bolts. This area is usually less than 12 feet in height and 5o x 8o feet in area but may be 14 feet or more in height and 8o x 100 feet in area when ground conditions are favorable. This volume is then filled and the process repeated by mining any higher ore by the same methods. Slushers move the ore in both mines to raises or loading points from which track haulage equipment trams it to the shaft.

## SUMMARY

Early attempts to attain relatively high rates of ore production rapidly were not a success in wet mines in the Ambrosia Lake area, and were very frustrating to the operators. Many of the early difficulties have been solved by obtaining a much better concept of the ore-body confines before beginning full-scale production. Operating costs, safety, and working conditions have been greatly improved by draining ground water from the ore-extraction areas before entry, and changing from trackless to track equipment for main haulageways.

Some of the problems still under study include more complete recovery of ore, improvement of safety practices, reduction of ore dilution, and improved methods of mining the thicker ore bodies, especially when a large area is involved.

# *Production Geology Methods at the Kermac Mines*

FRED C. HOHNE

## INTRODUCTION

The preceding papers on the geology of ore bodies in the Ambrosia Lake area indicate that they are erratic, discontinuous, and nonhomogenous. The largest deposits are below the water table and the host rock is soft, friable, and unconsolidated. The physical problems attached to mining, coupled with the random distribution of the ore bodies, result in high costs, low efficiencies, and poor extraction. The success of a mining program is largely dependent upon well-planned development and efficient grade control.

## MAJOR DEVELOPMENT

The basic development of the mines, that is, shaft location, haulage elevation, and distribution, are planned from surface drill-hole information. In most instances surface holes are drilled on a i 50-foot grid. Fill-in or firespot-holes are drilled occasionally. With low-cost surface drilling, it is often more economical to drill a hole than to drive a drift to test an idea.

## DETAIL DEVELOPMENT

After the footwall haulage drifts are driven, they are "long-holed" for drainage and exploration. Drainage is important to facilitate stoping and to increase the strength of the rock. Exploration is required to preplan the stope development, the position of manways and muck raises, and for service and ventilation facilities.

The long-hole fans are drilled on centers varying from 25 to 5o feet, depending upon the continuity of the ore. A long-hole fan usually consists of five holes, but more may be required, depending upon conditions (figs. 1, 2). The drilling is done with a pneumatic rotary drill manufactured locally by Machinery Services. EX diamond drill rods are used. The coal auger bits are tipped with tungsten-carbide inserts. The bits are sharpened as many as four times. Contract drillers average nearly 400 feet a day. Most of the drills are mounted on mine trucks especially adapted to carry steel and tools. The ore sandstone is extremely soft and easy to drill. Two-man crews have made in excess of 1000 feet a shift.

The long holes are probed by Century Geophysical on a footage contract. The gamma logs are returned to the mine office the day after the holes are probed. Precautions are taken to assure calibration and repeatability.

Fan cross sections are prepared from the drill logs (fig. r, 2). After preparing a series of fans, the geologist using the data plots a plan map ( 1 inch equals 20 feet) of the ore intercepts. For angle holes, the center of the ore interval is used as a plot position and the true ore thickness is recorded with its base elevation.

The plan maps often become extremely complicated by multiple ore layers, interbedded waste, faults, and abrupt pitches of the ore band. Familiarity with the ore distribution gained through the interpretation of the logs and map preparation qualifies the geologist to make a preliminary stope development plan. The details of this plan are discussed with the mine superintendent, who either accepts the plan or recommends certain changes. The final plan is then discussed with the production superintendent and foreman at the weekly planning meeting. Copies of the stope plan, with pertinent comments, are given to engineering production bosses and the grade-control engineers. Copies are also placed in the mine office and the bosses' lunch room underground. Daily advance and muckpile grades are plotted by the grade-control engineers.

## GRADE CONTROL

During the development phase, the grade-control engineers begin their important part in the production cycle. These men are graduate geologists or mining engineers. They are on shift work and are assigned to the same beat as the stope bosses, with whom they work very closely.

The grade-control engineers are briefed by the geologist on the detail stope development plans. Their duties then, as outlined in the Standards Manual, are as follows:

1. Guide-stope development and stoping except those headings being driven on a surveyed line. 2.
2. Probing of all broken muck.
3. Recommend the drilling and probing of test holes.
4. Maintaining muckpile maps, up and down hole maps, and other records as may be necessary (figs. 3, 4).
5. Maintaining close communication with all bosses within the assigned area. 6. Sampling.

The grade-control engineers are exposed to geology, engineering, and production. This position has been used to advantage as a training program for all three departments.

The grade-control procedures, as well as mining methods, change in ore more than 15 feet thick. In thin ore, the mine plan is basically as follows (fig. 5):

1. Drive muck raises on 1150-foot centers with a manway at alternate raise positions.
2. Sill on the base of the ore and with slushers drive from raise to raise and laterally to the edge of the ore on 3o-foot centers.
3. Access drifts are driven at the edge of the ore for tending blocks.
4. After two or three stopes have been completely developed, stoping begins with retreat toward the develop-

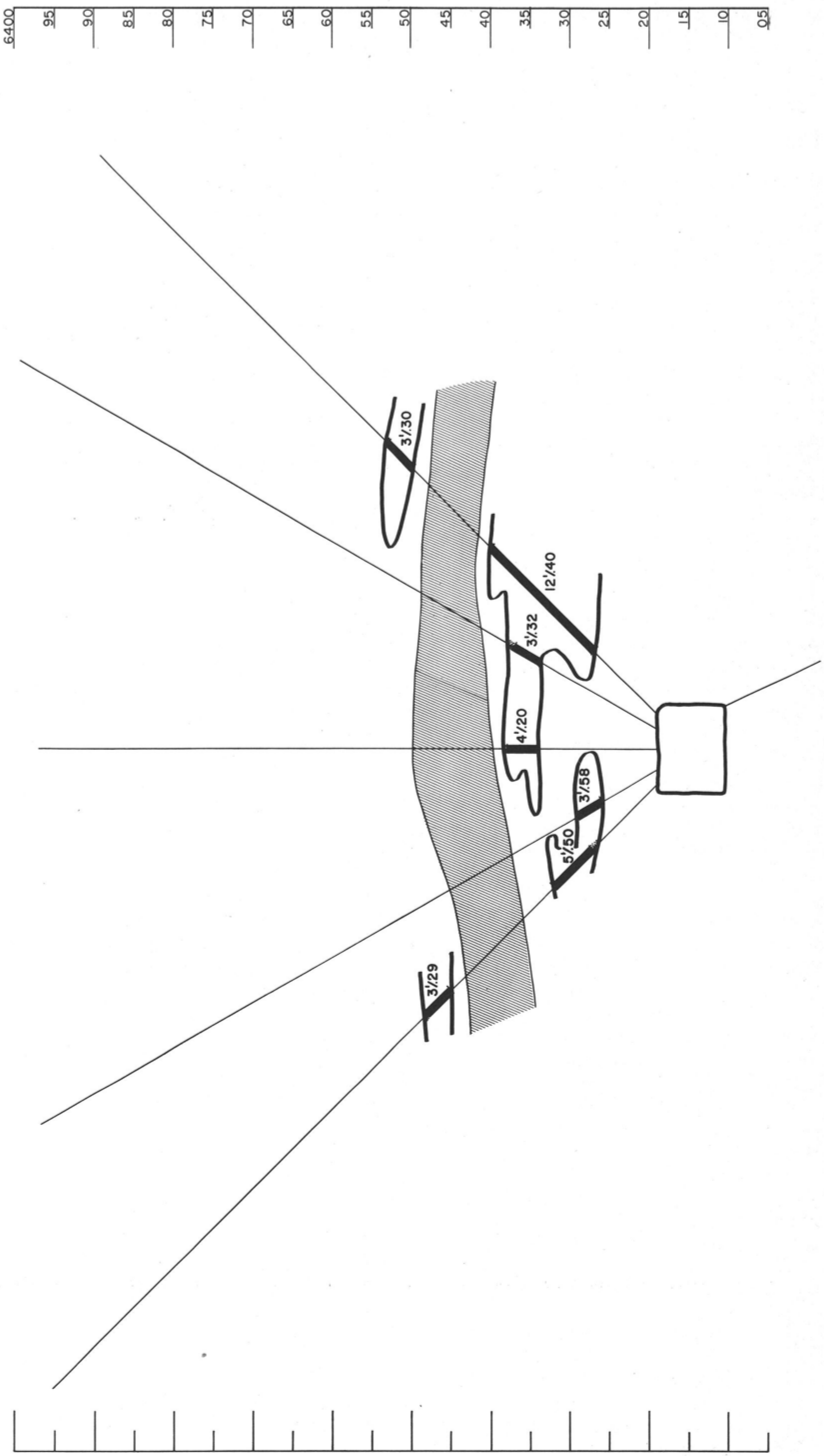


Figure 1

TYPICAL TREND-TYPE LONG HOLE FAN

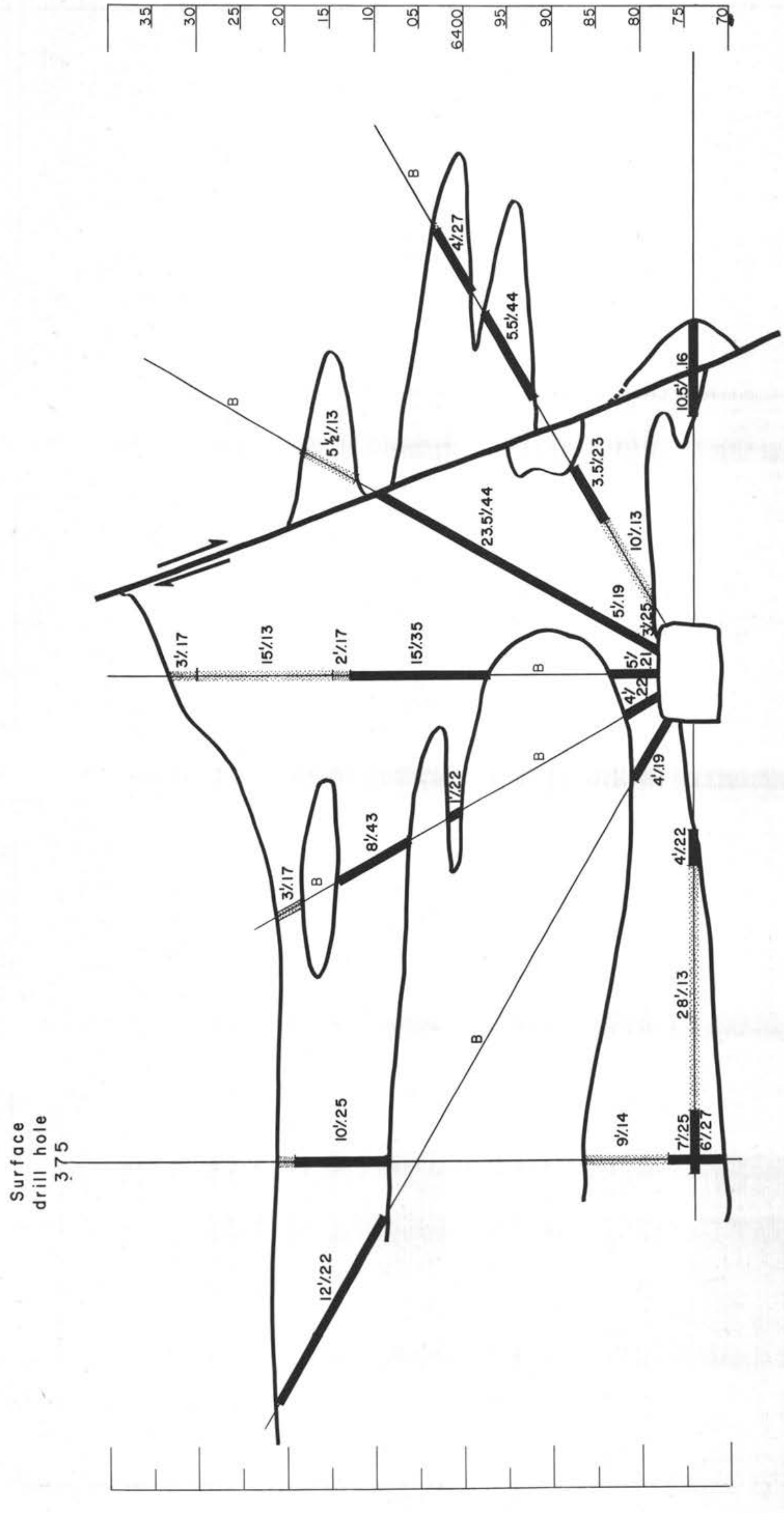


Figure 2

TYPICAL STACK-TYPE LONG HOLE FAN

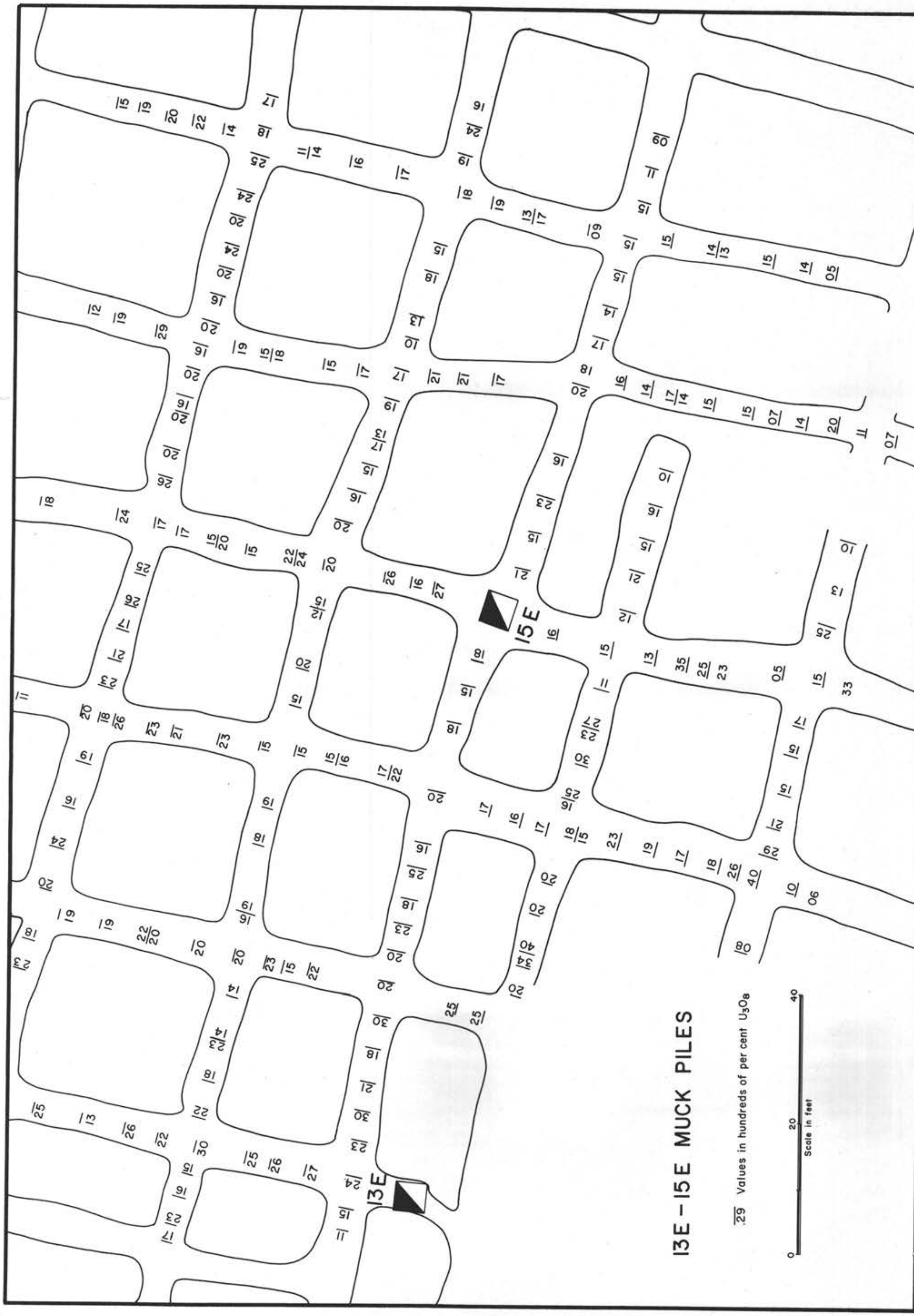


Figure 3

MUCKPILE MAP SHOWING STOPE DEVELOPMENT PLAN WITH AVERAGE GRADE OF ORE FROM PROBE RESULTS

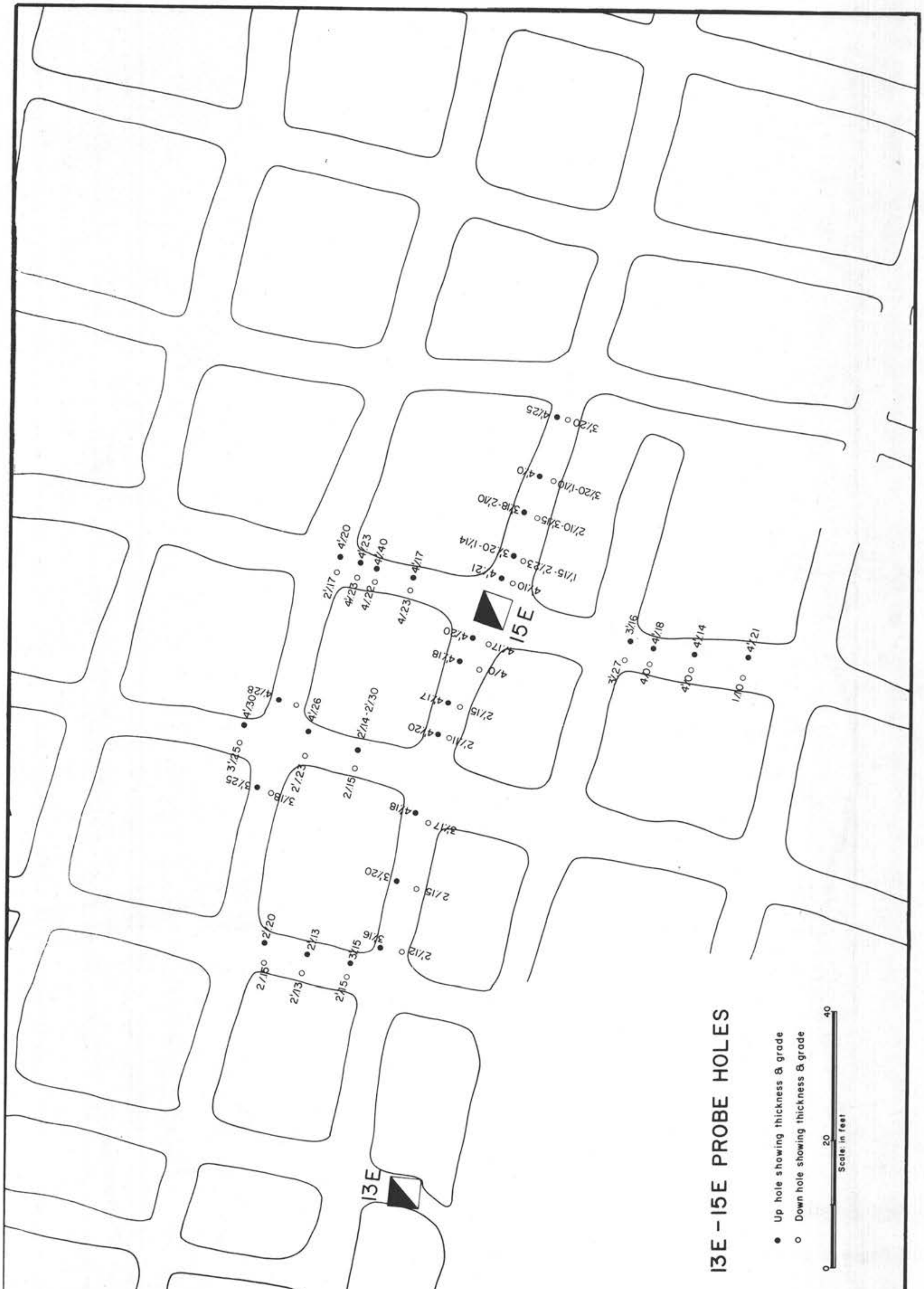


Figure 4

PROBE-HOLE MAP SHOWING LOCATION AND VALUES OF ORE IN THE BACK AND SILL

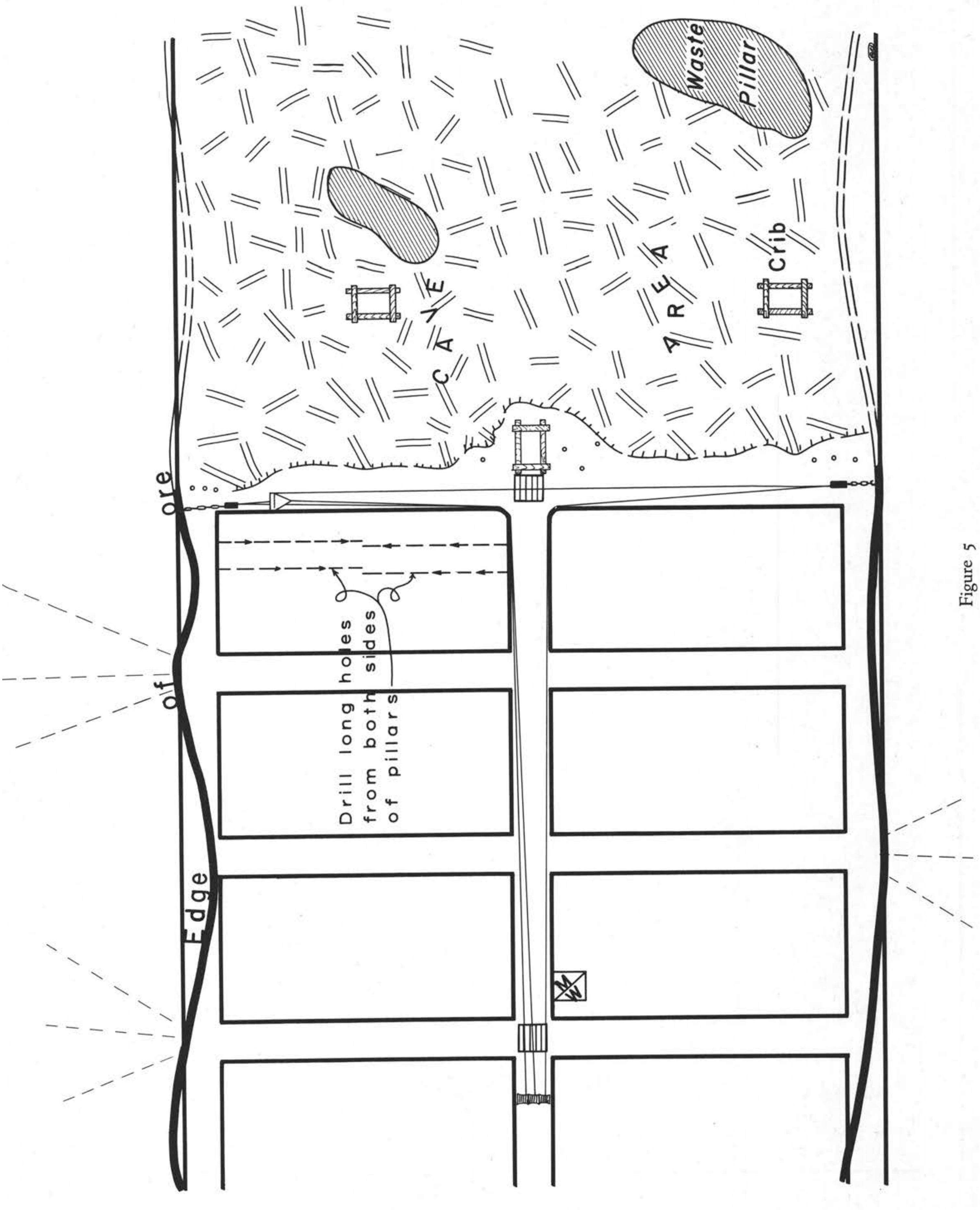


Figure 5

STOPE DEVELOPMENT PLAN SHOWING STOPING PHASE AND EXPLORATION DRILLING FOR ORE EXTENSIONS OR PARALLEL TRENDS ment headings, not necessarily from property lines toward the shaft.

The geology and grade-control procedures for this method of mining are as follows:

1. Sill elevations are provided for the engineering department.
2. Each round is plotted on the advance map along with the average of five probe readings for the muckpile (fig. 3).
3. Prior to drilling a round, the miner drills a 6-foot vertical hole. This hole is probed and plotted on the appropriate maps (fig. 4). With this probe information, the geologist can advise the miner whether to go up or down in order to stay on the bottom of the ore.
4. Before laying out the access drifts, alternate stope development headings are "long-holed" with 100-foot holes. If no parallel trends or ore extensions are found, access drifts are planned at the assay cut-off (fig. 5).
5. Pillars are marked by the geologist as ore or waste. The pillars are blasted with long-holes which are probed by the geologist prior to blasting. If waste is anticipated, the blasting fan-hole pattern is sometimes drawn up by the geologist.

Assuming that an ore body is 5o feet in thickness, the grade-control procedures as well as the mining plan must be altered to meet this condition. After preliminary development on the base of the ore, the mine plans call for the establishment of a slot from top to bottom of the ore and then for ring blast holes to be drilled from a drilling drift through the center of the ore body. Since the grade-control engineer cannot go into the open stope to probe a muckpile, key holes in each ring are probed by Century or with a hose probe. The holes are used primarily to determine the cut-off for loading and blasting but are also used to calculate the grade of each blast.

Dilution in large, open stopes is to be expected and cannot be avoided. The grade of this caved material cannot be controlled, but when the muck is probed at the raise and found to be waste, either slushing is stopped or the muck is loaded as waste.

Scram drifts with finger raises are used for ore more than 5o feet in thickness (figs. 6, 7). The grade-control procedures for scram drifts are as follows: Each finger raise is probed and grab-sampled twice each shift. The samples are bucked at the mine and assayed on a Beta analyzer. Fingers which run waste are blocked off, or ore fingers may be blocked off and waste is pulled until the probes indicate ore, at which time all fingers are pulled together.

## GEOLOGIST'S RESPONSIBILITIES

Geologists are responsible for

1. ore reserve calculations
   (a) long-hole reserves
   (b) developed reserves
   (c) surface drill holes (probable)
2. production records
   (a) prediction sheet
   (b) daily stope production and grade
   (c) calculations of percentage extraction by pounds, by tons
3. supervision of long-hole drilling program
   (a) contract drillers
4. underground mapping and correlation
5. besides their normal duties, geologists participate actively in mine planning.

These responsibilities are more or less standard for mining geologists, except perhaps item 2, production records. The prediction sheet is a form filled out by the superintendent and geologist at the beginning of each month. It lists the working places and the tonnage and grade expected from them. The form is divided into weeks and the actual production from each week is entered beside that predicted, for a comparison. The form is useful in that it requires preplanning and provides a measure of performance.

Permanent records are maintained as to the source of daily production and grade, 2 (b). This information is used to calculate the percentage of extraction based on tonnage and on pounds of $U_30_8$.

## ORGANIZATION STRUCTURE

To have an effective geology and grade-control program, the department must be set up as a staff function. To avoid misunderstandings and possible causes of friction, the duty, authority, and responsibility of all technical and supervisory personnel are defined explicitly in a Standards Manual. Their relationship to the other departments and supervisors is thoroughly understood.

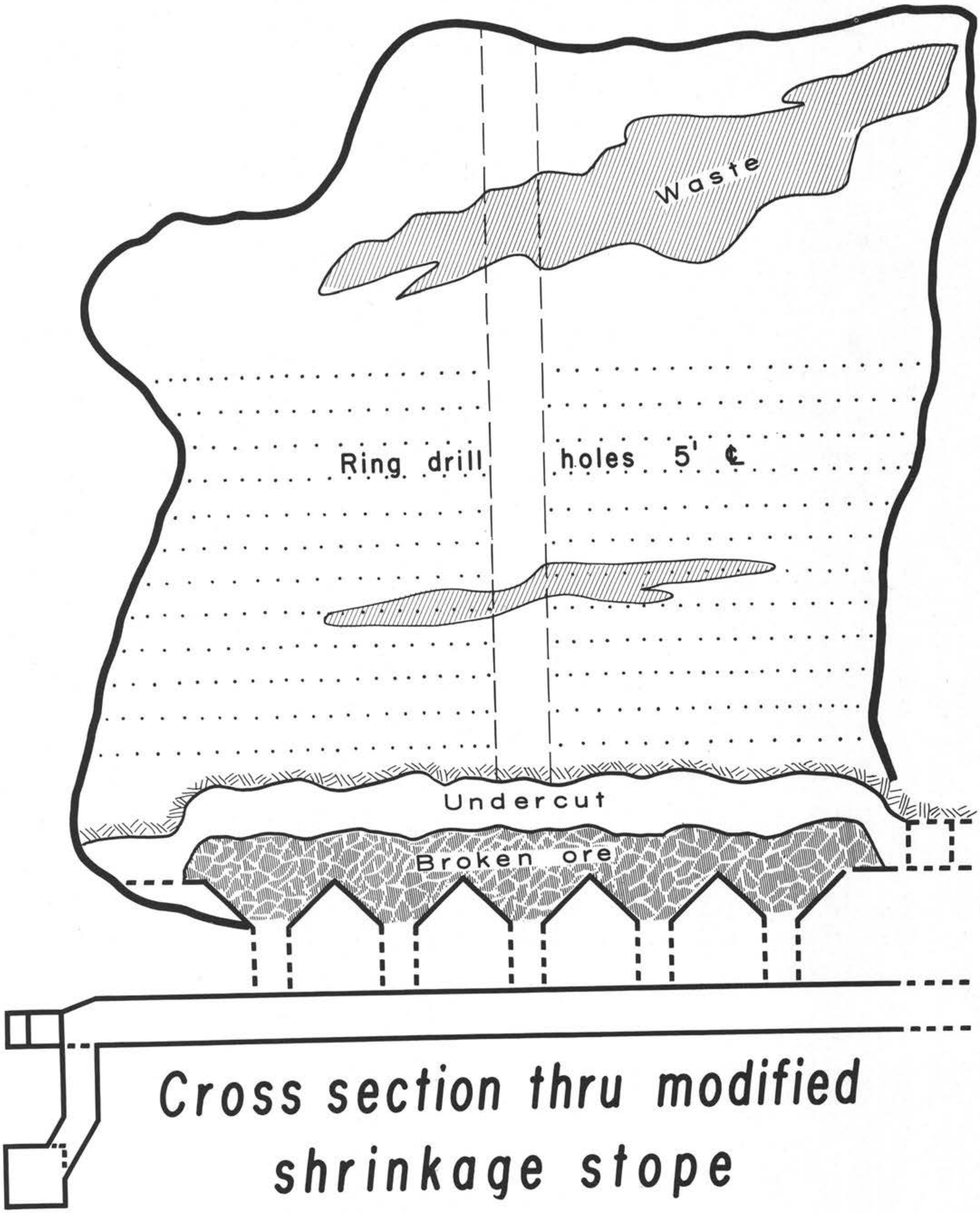


Figure 6

CROSS-SECTION THROUGH STACK TYPE ORE BODY ILLUSTATING MINING METHOD

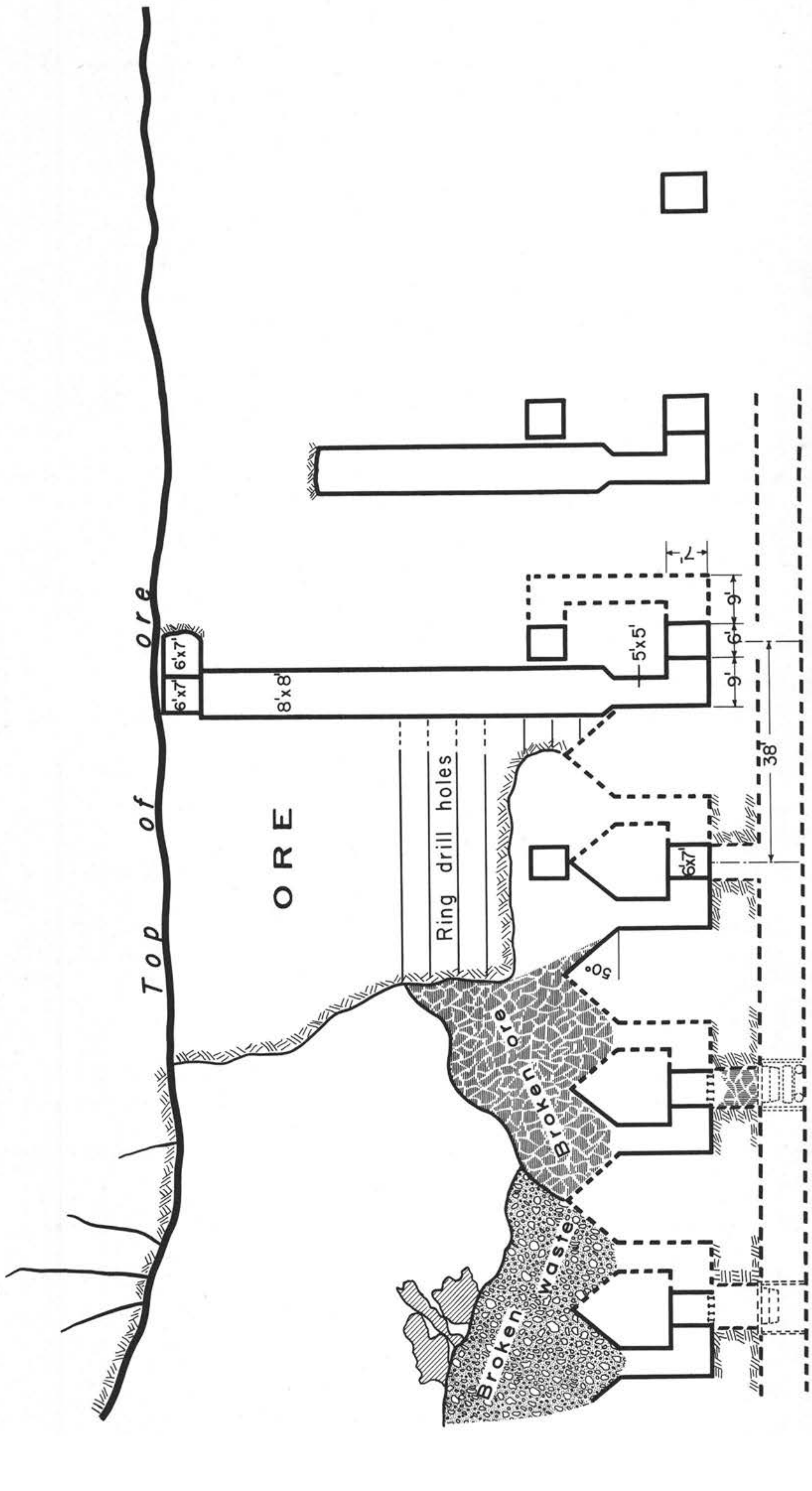


Figure 7

Longitudinal section through stack-type ore body showing development and stoping procedures

# *Subsidence and Pillar Recovery in the Vest Area of the Marquez Mine*

GLENN C. JOHNSTON

## INTRODUCTION

The Marquez mine, operated by the Uranium Division of Calumet and Hecla, Inc., is about 24 miles northwest of Grants, New Mexico, in sec. 23, T. 13 N., R. 9 W., McKinley County. The Marquez ore body lies in the southeastern end of the Ambrosia Lake area and was discovered early in 1955. Entrance into the ore body was started in August 1957. The Marquez was designed for a total material output of approximately 500 tons a day.

Access to the ore body is by an 800-foot incline of minus ten percent grade. Inside clearances are 9.5 feet high by 14 feet wide. The incline was driven on contract by Febco Mines, a local mining concern, and was completed in February 1958. Development began immediately toward the west to intercept the largest tonnage of the high-grade ore contained in the ore body (fig. 1).

The ore has the same general characteristics as that of the main part of Ambrosia Lake area. It occurs in sandstone and is usually black. The thickness ranges from one to 24 feet and averages eight to nine feet. It lies essentially flat, but haulageway grade changes of a maximum of ten percent up or down were usually sufficient to carry the bottom of the ore horizon. The depth from the surface to the bottom of the ore zone is 180 to 270 feet.

The ore occurs in the Poison Canyon sandstone of the Brushy Basin Member of the Morrison Formation. The stratigraphic units (fig. 2, vertical section) in the Marquez area are as follows, from top to bottom: about 70 feet of Dakota Sandstone; about 120 feet of Brushy Basin sandstone, shale, and mudstone; about 20 to 60 feet of Poison Canyon sandstone; and 25 to 30 feet of Brushy Basin mudstone, all underlain by the Westwater Canyon Sandstone.

In the West Area, the ore zone contains mud and shale

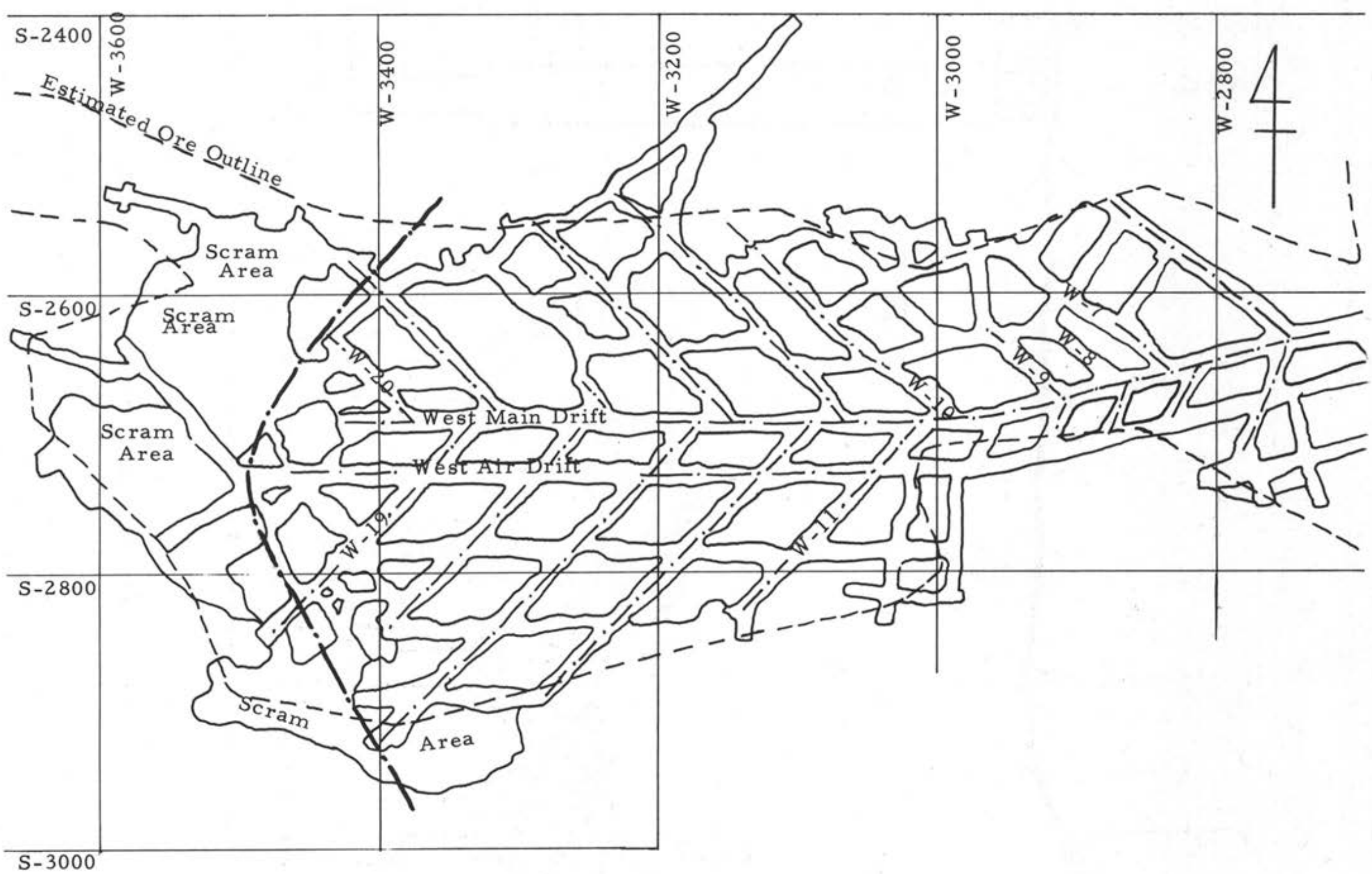


Figure 1

WEST AREA MARQUEZ MINE

Drift and center lines show original development plan of drifts and crosscuts.
Dark broken line denotes expected change from slushers to the larger loading and trammer equipment.

seams of no definite pattern or consistency, and there usually exists at its base a "hard zone" of calcite-cemented sandstone. The ore zone varies from six inches to four feet in thickness with an average of two feet and is generally good ore.

## DEVELOPMENT

The mine area under consideration was originally dry, except for a very small part on the northwestern end. In the planning stage, it was decided to enter and develop the mine within the ore horizon using mobile equipment for loading and hauling, 51/2- to 6-ton trucks and crawler loaders. The Eimco 63o, electric, was the prime loader. The TD-9 International Harvester front-end loader and 933 Caterpillar were to be used for moving of equipment, bulldozing, and scraping and as auxilliary loaders. Wagner loaders were added early in 196o. Slushers were to be used in the low fringes. Main haulage and cross haulage drift dimensions, dictated by mobile equipment dimensions, were 9.5 feet high and 13 feet wide. In the early stages of development, drift sets of 10 x 10 inch ponderosa pine were used for support. The headings were carried 10.5 to 11 feet high by 15 feet wide with flat backs. Shortly thereafter, roof bolts were used for back support, cutting the size of the drifts to 9.5 to Io feet high by 13 feet wide.

The western section was opened by the Main West Drift and supplemented by the West Air Drift paralleling it for ventilation purposes.

Cross haulages were turned off at 45 degrees on 8o-foot centers, the angle mentioned being the most practical for the truck haulage. Drifts on 8o-foot centers, parallel to Main West Drift, were turned off the cross haulages. This pattern left pillars 6o x 6o feet along the ribs, but only 45 x 45 foot effective dimensions. Variations in the pattern were due to variable thickness of ore, various widths of the ore body, horses of waste or low grade, and irregularity of the fringes. As the ore thinned toward the fringes, development continued with slushers. Minimum height carried in slusher scrams was 4 1/2 to 5 feet.

## RETREAT

Retreat was planned to start at the western extremity, progressing eastward to the shaft. The cave line was to be on a north-south bearing. The initial pull-back was done by slushing for about 14o feet. The remaining retreat to the eastward was with mobile equipment, combined with three drum slushers. The method was to cut pillars by crosscuts and recover remaining stubs. The line of demarcation between the two systems of equipment usage is roughly marked on the map (fig. 1). Thickness of the ore was the sole determining factor at that time.

Electric slushers from 10 to 30 h.p., 36- to 48-inch buckets, and 1/2-inch cable were used. The maximum slushing distances were 18o to 190 feet. The ore was pulled to muck pockets in the main and cross haulages and then loaded into trucks.

The two mining methods used in the slusher areas were modified long wall and modified room and pillar. In both instances, all crosscuts were carried eight feet wide, which is the average maximum width that could be kept open without roof support. In the room and pillar system the crosscuts were on 32-foot centers. With retreat, these large pillars were cut into 8 x 8-foot pillars and 8-foot crosscuts, against the stope line only. This left small, fast-pulling pillars to expedite productivity and, at the same time, allowed massive pillars ahead to absorb the weight caused by cantilever action of the cave. In the long walling, the 32-foot pillars were walled off

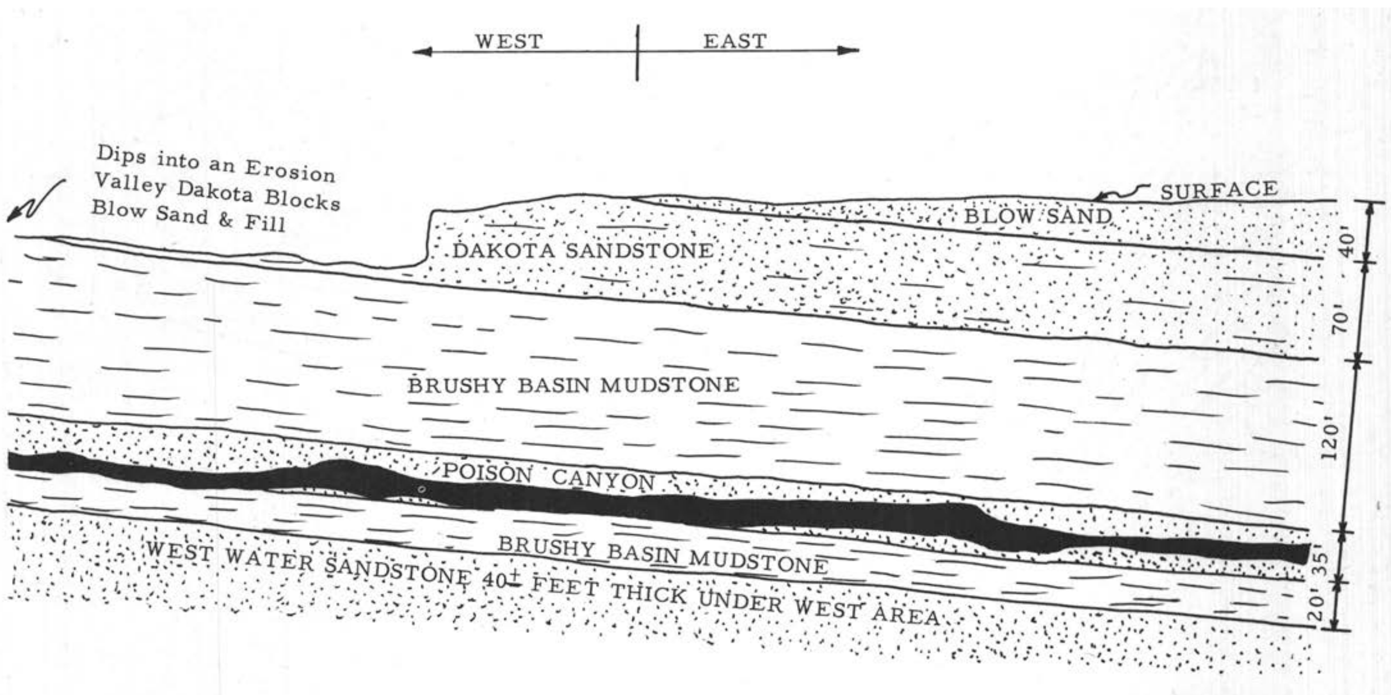


Figure 2

SECTION WEST AREA MARQUEZ MINE

**NOTE:** Poison Canyon Sandstone is the producing member (ore is shown in black). Dip of beds is about 6 degrees northeast.

parallel to the north-south cave line and slushed to the main east-west slusher scrams. The latter method gave better extraction but very poor productivity. Stulls were hard to hold as they would not tighten up adequately until they took weight. This resulted in repeated restulling, refencing, and reslushing for cleanup. With weight, the backs broke into thin slabs above and between stulls.

Thus far, caving action has been achieved and some overthrowing of weight had been caused by cantilever action, although it had not been serious. The sandstone floors had not heaved. It should be mentioned here that caving (sandstone backs) did not usually start in the West Area before an area of 60 x 40 feet was extracted (a 60-foot minimum width along the cave line must be maintained in the retreat to insure proper continuance of the cave). With soft shale and mud-stone backs, this figure diminishes to as low as 20 X 20 feet. In the South-4, South-I mine area we open up about 125 to 150 feet on a side before true cave action starts, because of the more competent and thicker sandstone backs.

The telltale slabbing and cracking of the ribs that indicates a new cave action is noticeable from a few hours to a day or two ahead.

A fairly straight cave line was managed after 140 feet of retreat (fig. 3, A-A). At this point, however, choice between a delay at Point "B" (fig. 3) and stopping the rest of the stope front or chancing a curved cave line had to be made. Ore commitments dictated the latter.

One ore pod (Point "B") was 18 feet thick and about 40 x 50 feet in size. This area had taken some weight. It was topped by soft shale and bottomed by mudstone and a "perched" water table. Its high-grade character dictated extremely clean mining and high recovery. As a result, it was necessary to square set instead of using the much faster crosscutting and stub pulling with mobile loaders and three drum slushers. Bottom heaving was evident for the first time in this area.

Retreat in the southwest portion was continued, finishing off the slusher areas of the fringe and experimenting some with thick pillar pulling using mobile loaders (fig. 3, new cave line). The remaining ore to the east now was bottomed by mudstone. Surface seep water was now trickling through the cave area in large amounts and following the retreat front. The cave line seemed to conform temporarily with the curved stope line. The square-set area was finished and the cave front straightened. During this period the entire West Area began to move with pillars settling into the mudstone and the bottoms heaving, en *masse*. Figure 3 shows the extent and shape, fulcrum area, and so on. The floor heaving was rapid, in some places more than six inches a day. "Hard zone" ore had been left in the floor of some areas to be ripped out on the retreat. These bottoms failed, cracking down the centers of the drifts and cross haulages, then breaking up at right angles to the original crack. For the most part, except for drift and crosscut intersections and pillars adjacent to the stope line, the pillars and backs did not break up. The acute angle corners of the

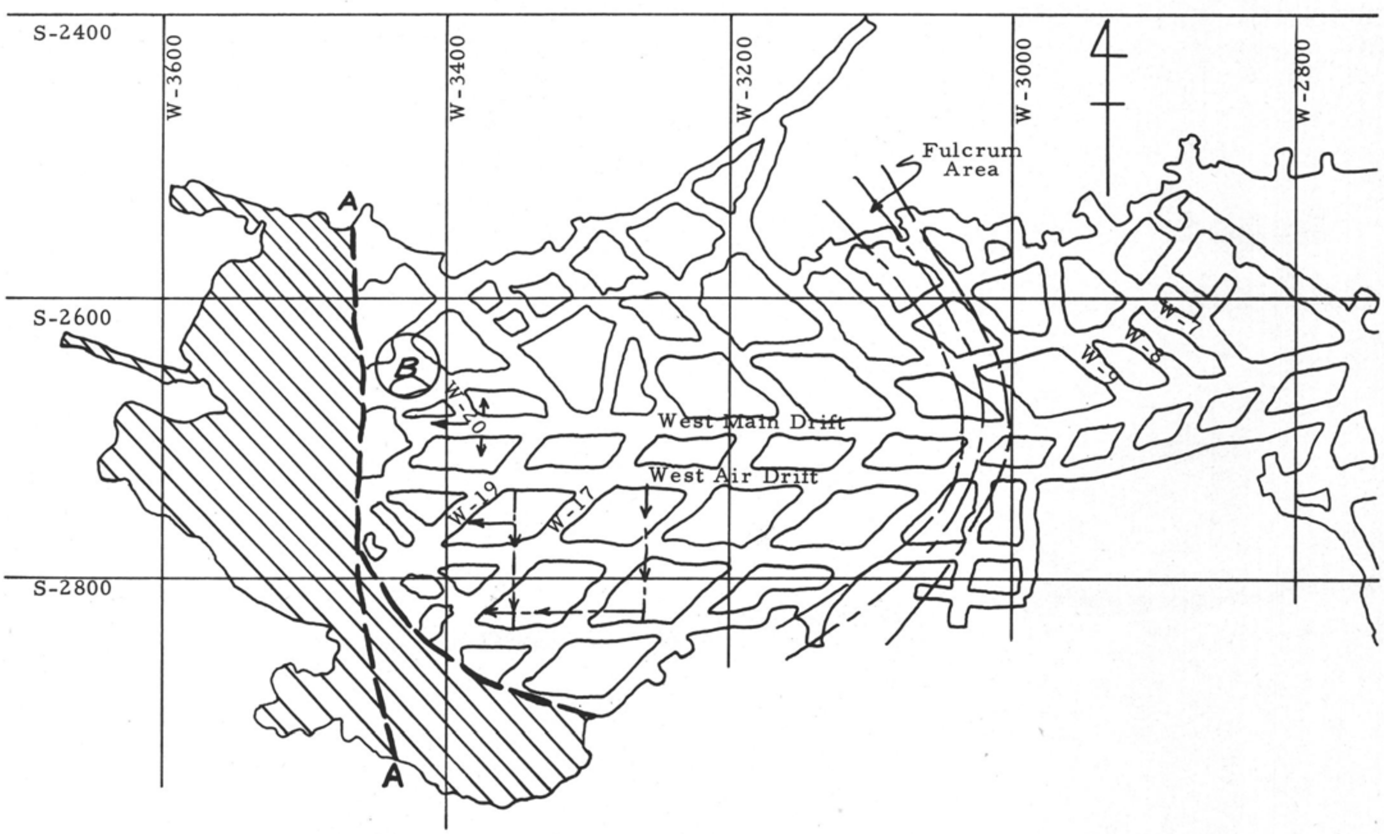


Figure 3

WEST AREA MARQUEZ MINE

Extracted area—Crosshatched. Caveline—Dark broken line.

pillars and some high ribs "flaked." Simultaneously with the initial movement, vertical tension cracks opened in the backs of the crosscuts and drifts. These were single cracks down the centers. There was virtually no differential movement along these cracks until September 1960.

The pillars settled on an average of o.15 foot a week from the end of January to about mid-March 196o (fig. 4). The total average subsidence to September 1960 was about 4 to 4 1/2 feet, an over-all average of approximately 0.1 foot a week. There is still movement to this date.

The immediate remedial actions were to timber the intersections and few accessible stops with cribs, sets, stulls, pin-up caps ("monkeyward" caps), or their combinations, depending on clearances needed. The drift and crosscut straightaways were stulled along the ribs. The roof-bolted backs held well (some are still in good condition), except, again, in the intersections. It was learned early to place the stulls and posts into the mud bottoms and thus allow mudstone to flow up around them. Sandstone bottoms or foot boards buckled heavy timbers during a shift. Periodically, the bottoms were scraped down for necessary head room. Incidentally, very few caps were broken and none was broken from differential movement of the backs.

It soon became evident that mining could not keep up with the heaving action and still produce economically. Adequate openings involved much more work than was put into direct extraction. Considerable dilution resulted from bottom scraping. About March 196o, it was decided to close the West Area for observations and analysis.

Survey control points were established on the surface and underground. These points were checked weekly to ascertain the magnitude and rate of subsidence.

Core samples were taken from the underlying mudstone to determine moisture content, compressive strength, effects of water, and so forth. The important properties of the undisturbed mudstone were as follows:

1. Moisture averaged 15 percent.
2. Compressive strength, 200 psi with sustained load.
3. Disintegration in water, a few minutes, with large volume increase.

It was decided to consider ( 1) the method of stabilization and (2) the method and conditions of continued mining. Also stabilizing wet and dry sand fill, cribs, grout, and freezing were considered. Wet fill was rejected on these counts: (a)

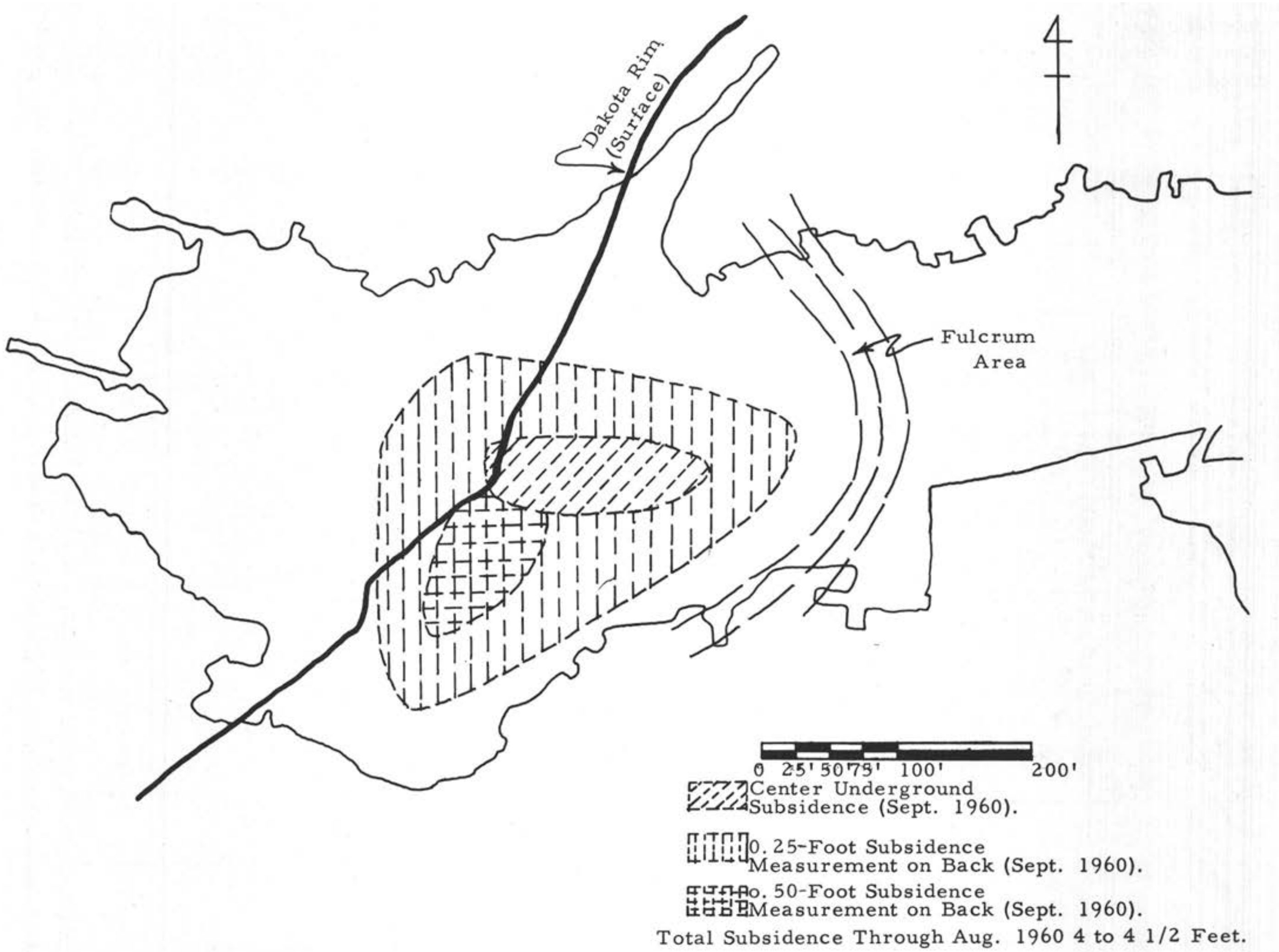


Figure 4

WEST AREA MARQUEZ MINE

effect of water on the mudstone, (b) time and capital necessary to build a surface classifying plant, and (c) pumping problems underground. Grout and freezing were impractical and costly. Dry fill (plus cribs) was decided upon because of (a) ready unlimited supply of blowsand on the surface, directly over the ore body, (b) ease and speed of drilling the 13-inch bore holes to funnel blowsand to underground workings, and (c) much lower cost with respect to the other methods considered.

Open-pitting of the West Area was seriously considered, but analysis of the costs showed it was not feasible. It was then decided that once the fill program was far enough along to stabilize the affected area and the Main West Drift and West Air Drift were secured for safe passage, we would attack the retreat in two places as follows (fig. 3):

I. Drive south of West Air Drift into West-17 crosscut and west to the old stope line. Retreat all that lay to the south of West Air Drift.
2. Work off the end of West Drift at West-2o, retreating everything north of the West Air Drift.
3. Work these two locations on a three-shift basis.
4. Use a drift-slicing method of extraction (similar to top slicing, but with stope development at a minimum).
5. Continue fill behind developed-unextracted area to the east, at least as fast as stoping progressed.

Approximately 4o percent of the total ground was extracted from the West Area during development. It was considered that filling 5o percent of the remaining haulages would stabilize the area or, at least, slow up heave and subsidence enough to be able to continue mining.

The filling operation consists of dropping dry blowsand down 3-inch bore holes into trucks, transporting it to the fill area, and back-filling with Wagners or "Cats" and slushers. It is difficult to form a tight fill without excess hand labor; therefore, cribs often take the place of the fill in the last two or three feet next to the backs.

The initial stoping was Blusher ground, pillars were badly crushed, and head room low. The timbered drift slicing was carried in a north-south direction. The original plan was modified by leaving a five-foot pillar between drifts. This pillar

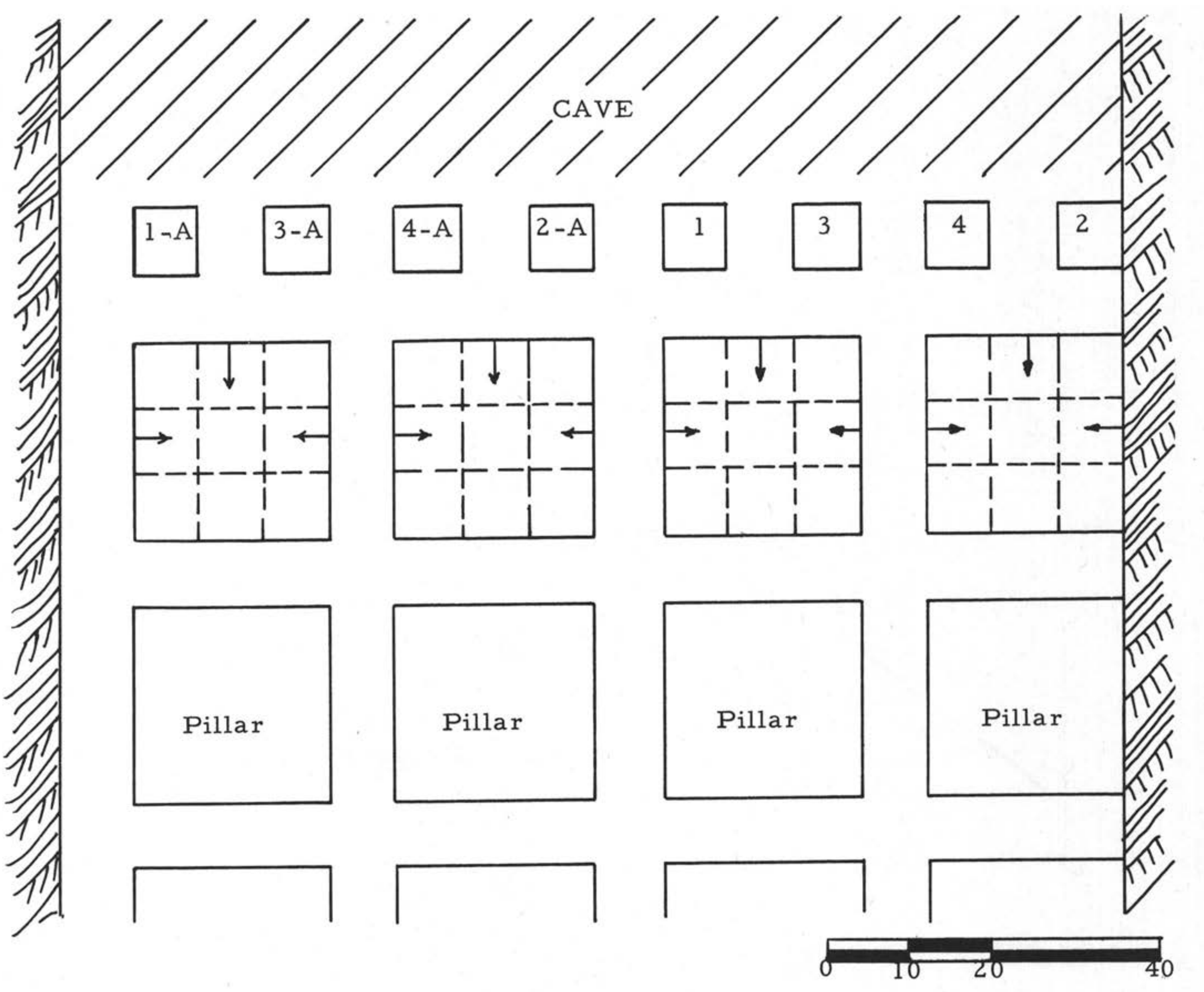


Figure 5

MARQUEZ MINE PLAN ROOM AND PILLAR MINING METHOD was partially recovered once the drift was finished. Care was taken to drive and finish one drift at a time. When predeveloped, too much floor was exposed, heaving accelerated, and the stope was usually lost.

As retreat progressed to better ground, the cross sections of the drifts were increased to accommodate Wagner front-end loaders in the stopes. A portable Blusher was available as an alternative to mobile loading and for clean up. West Area end productivity tripled under these conditions. However, this was short-lived, and backs and pillars started to crack up slowly. Sudden ground falls were never experienced, except in the already caved areas, but that sudden falls would not occur, could not be predicted. It was decided, therefore, to return to smaller access drifts, more timber, and slushers, in the interest of safety.

In the near future, the retreat will be back on higher ground with the chance of leaving the water behind. The percentage of fairly solid pillars will be greater. Another attempt will be made at Wagner loading in the stopes. Slow heaving and settling is expected to continue back to West-7 (fig. 3) where the sandstone bottom begins.

## SUMMARY

This paper has been an attempt to evaluate objectively the natural setting and imposed conditions that led to the subsidence of the West Area of the Marquez mine.

From past experience, it is hoped that mining of the remainder of the ore body will be more orderly. The reasons for surface subsidence at the Marquez mine appear to be caving of the mined-out area and the unextracted area settling into mudstone. The first had little effect. Both surface and underground control points show 4 to 4 1/2 feet of subsidence over unextracted ground. The maximum total subsidence over the West Area is 4 to 4 1/2 feet. The conditions leading to pillar subsidence may be outlined as follows:

Natural setting

a. Incompetent mudstone underlying comparatively competent ore zone.
b. Natural water course from surface to this same impervious mudstone. This course was caused by an old erosion gully cutting down through the imper-

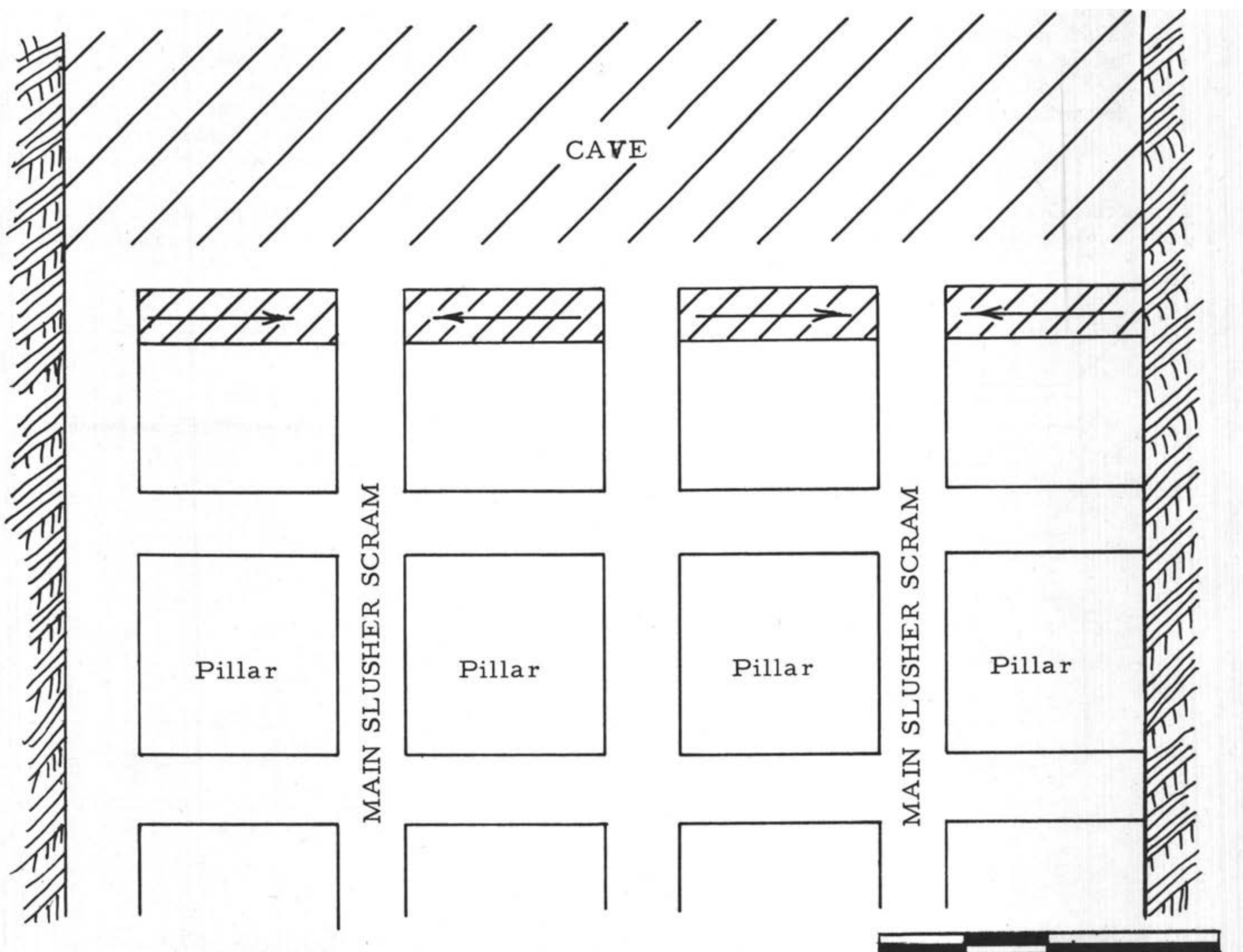


Figure 6

MARQUEZ MINE LONG WALLING MINING METHOD

vious Brushy Basin Member overlying the ore zone. Water is not considered as a cause, but it facilitated the movement, once started. The water definitely slowed mining.

2. Imposed conditions due to mining
   a. Pattern and pillar size. The same general setup was adequate to maintain rigid floors in the other mine areas, but it definitely was not adequate for the area under consideration.
   b. Curving the stope line. Swinging the stope line abruptly into the south fringe probably started the settling in that locality, as it left the two sides of the corner unsupported. The competent Dakota Sandstone did not fail immediately, causing the cantilever action to the east and northeast.
   c. The north and south limits of the West Area were completely fringed with crosscuts. The pillars adjacent to them were comparatively narrow. Evidently the stress set up roughly parallel to and above them was enough to cause the failure started by curving the retreat line. This formed a "floating peninsula." The Dakota soon snapped at the fulcrum (fig. 3), forming a partially independent island of the ore body. The fractures at the fulcrum run roughly north and south, curving back to the northwest and southwest. This fracture zone is nearly 4o feet wide, east to west (West-I1 to West- o).

## GENERAL COMMENTS

It cannot be said that subsidence would have been positively avoided by maintaining a straight stope line. Before mining, the ore horizon was under a 200-psi stress. Mining raised it, in some areas, to 400 psi. The least expected would have been heaving and settling along the stope line and possibly as much as 5o feet or more ahead toward the east. This is pointed out by the fact that slight heaving was encountered well to the east of the fulcrum point in undisturbed ground (West-8 and West-9). No measurable settling was noted there (fig. 3).

It is unlikely that pillar shape influenced settling. It did, however, influence adversely the facility for carrying a straight line cave. Once the pattern is set, the bearing of the cave line should coincide with one or the other side-wall bearing. The ideal is to square off pillars to a predetermined retreat. Right-angled pillars resist weight and movement. Acute-angled corners fail with slight weight or movement.

Percentage of extraction in the development stage has an important role regarding possibilities of settling when an incompetent floor is present. In this instance, the West Area was decidedly in delicate balance at the time development was completed. Little was left to trigger the subsidence. Possibly 25 to 3o per cent less open floor area in the development stage would have avoided the subsidence. This would have left only about 25 to 3o percent of total West Area possible to mine during development.

## FEBRUARY 1963

As a sequel to the above report, it is interesting to note that the method of fill and mining proved adequate to complete the retreat of the affected area, and this was realized in August 1962.

Heaving of the clay bottom diminished drastically; scraping for equipment clearance was cut to two or three shifts a month.

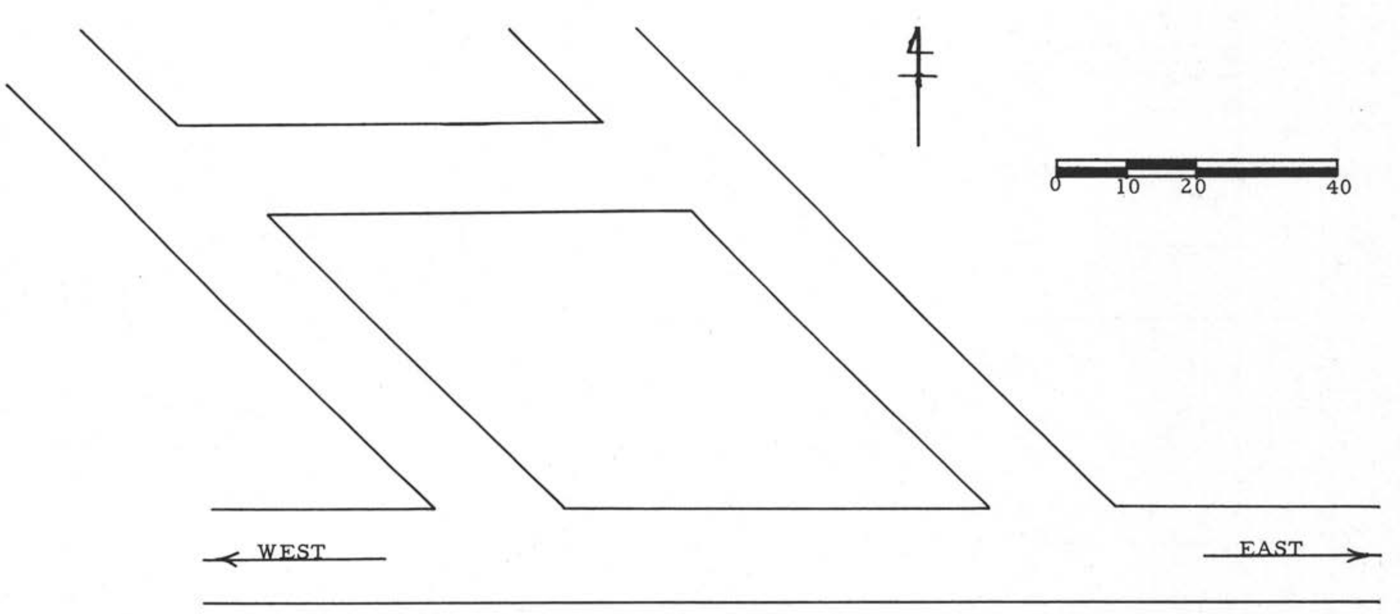


Figure 7

MARQUEZ MINE WEST AREA PILLAR DESIGN

Height 6 feet plus, Mobile Equipment

NOTE A: Methods of Extracting Pillar. 1. Crosscut pillar both ways, parallel to original ribs, then pull stubs. 2. Crosscut in a N-S direction to Main Drift starting on west corner: 10 to 12 feet width. Use method No. 1 when no weight present. Use method No. 2 when ground takes weight and when cave is followed.

NOTE B: 13 feet drift width at 8o feet centers at 45 degrees gives a 6o x 6o foot pillar. But, only a 45 x 45 foot effective pillar. The two acute-angled corners are lost under heavy ground conditions.

It was now an advantage, keeping timber sets, cribs, and stull tightened up against blasts and side pressures from crumbling pillars. Heaving action stopped completely at about W-7 where competent sandstone tongued in between the ore horizon and the mudstone. The timbered drift-slicing in a north-south direction, supplemented by cribs and stulls, was successful. Openings large enough for our mobile equipment (8 feet to 10 feet by 8 feet to 10 feet) were maintained about 80 percent of the time; slushing supplemented the remaining 20 percent.

Extraction of the remaining reserves of this area was about 85 percent.

The writer acknowledges the cooperation of the entire mine staff of the Marquez mine; of William Hays and Joe Longacre from the office of the New Mexico State Inspector of Mines, for remedial suggestions in the interests of safety and operations; of C. A. Campbell, George F. McKereghan, John Lasio, and R. W. Kliebenstein who directed the analysis and planning for remedial action; and of Niles Grosvenor, consultant, Colorado School of Mines.

# *Mine Safety Problems*

H. J. ABBISS

Because of the number of fatalities and serious accidents that had occurred and continued to occur in the uranium mines near Grants, it was necessary in the early part of 1960 to take drastic steps to rectify this situation. A group of individuals representing various uranium operations met to discuss the problem and as a result of this meeting, the Uranium Operators Safety Council was formed. In order that the council could function efficiently, the following program was instituted:

Membership is on a voluntary basis limited to those companies actively engaged in developing, producing, or processing uranium ores. A member company must actively participate in the program and appoint one representative to serve on the council.

The objectives of the council are to

(1) foster safe working conditions and practices in the mines and mills of the uranium-producing area of New Mexico;
(2) work and cooperate with the State Mine Inspector in all matters pertaining to safety, particularly with regard to the establishment of new safety regulations or the modification of existing ones;
(3) gather statistics on safety performance within the area concerned;
(4) afford a means for the interchanging of ideas and information relating to safety programs;
(5) administer and operate the Ambrosia Lake Mine Rescue Station;
(6) cooperate with member companies in safety promotion and in publicizing safety activities and achievements; and
(7) cooperate with other agencies interested in safety.

From an organizational standpoint, the council is governed and administered by a nine-man board. Meetings are held monthly, plus any special meetings that may be required. Minutes of each meeting are forwarded to all member companies.

Financing of the council is through the Uranium Operators Safety Council Fund. Payments by member companies are on an annual basis, the amount being determined at the first meeting of each year.

Just how effective was this organization in relation to the uranium industry in Grants? Fatal accidents were of primary concern, and so meetings were arranged for the purpose of obtaining as many facts as possible relative to mine accidents which had occurred in the Ambrosia Lake area since 1957. At these meetings persons having an intimate knowledge of the accidents gave detailed reports on all the facts surrounding them. A sizeable number of technically trained mining personnel attended the meetings, at which the following recommendations were made in the interest of preventing similar accidents in the future:

(1) All supervisors should carry a small bar to be used for sounding and scaling. This would encourage supervisors to be constantly aware of the necessity of sounding back and barring down. Also, it was thought that this would make the workmen more aware of the necessity of good barring-down procedures.
(2) Underground workmen should be trained in the general problems of rock failure and pressures so that they are thoroughly familiar with the fact that in this ground, barring once a shift is not adequate and that the back and ribs must be checked at frequent intervals, especially in or near stoping operations. It was thought that this could best be accomplished either at safety meetings or by the supervisor on his regular rounds.
(3) A general tightening up of enforcement of disciplinary measures by supervisors for poor bar-down procedures should be instituted.
(4) In some operations, the use of a special bar-down man should be considered. However, discretion must be used so that there is no possible feeling created that a workman is not responsible for making his own working place safe.
(5) Development and stope planning should be carried out in such a manner as to avoid small pillars which may fail when weight is exerted upon them.
(6) Development and stope planning should be carried out so that access to tail blocks will be safe and protected.
(7) While extracting pillars which are under pressure or could come under pressure, face and rib protection while drilling are to be given consideration.
(8) In a number of operations, greater emphasis should be placed on support to corners and ribs.
(9) Development and stope planning should take into consideration failure along fractures when the ground is subjected to pressure. Mapping all vertical fractures prior to stoping was recommended so that the locations of such fractures are known well in advance of stope planning.
(10) Operators should visit the stoping areas of a number of the mines in the area so that they will become familiar with rock mechanics in various situations and recognize the potential hazards that may exist.
(11) The Uranium Operators Safety Council should contact the U.S. Bureau of Mines to determine the results of recent studies in rock mechanics in the Ambrosia Lake area and make such information available to the members. The council should encourage further work by the Bureau regarding rock mechanics studies in the interest of safety.
(12) Each unit or operator should appoint an employee as a safety representative who should be registered with the State Mine Inspector's office.
(13) In some operations, a better formal safety indoctrination system for new employees should be adopted.
(14) First aid training should be compulsory, employees taking the training when requested to do so.
(15) Each new employee should work with experienced per-

sonnel until he is familiar with mining methods, types of ground, equipment, etc.

(16) Member companies should examine the records of prospective employees and refuse employment to any person who has been discharged for unsafe practices or who has a poor safety record.

(i 7) A code of basic safety rules and regulations should be adopted by the council, violation of which should be sufficient cause for immediate discharge of an employee.

(i 8) All operators should consider the use of safety incentive programs.

The majority of these recommendations were adopted and have proved extremely effective in reducing fatalities and serious accidents.

## EFFECTIVENESS OF RULES

Consideration was also given to the effectiveness of the existing State Code. It was felt that some of the rules should be revised and in connection with this, the State Inspector of Mines met and consulted with the council. New rules, such as the mandatory use of roofjacks at all underground headings, adequate use of roofbolts with chain-link fencing, additional timber support, again diminished the number of accidents in the mines.

Monthly statistics are submitted by all member companies to the president of the council. Computation of these reports is the same as for any other statistical data, except actual days lost are recorded instead of days charged according to ASA or NSC Standards. The standard charge of 6000 days for a fatal or total permanent injury is adhered to.

Inspection of Figures I to 3 demonstrates that preventive measures set up by the council have proved effective.

Frequent meetings of the board, which is comprised mainly

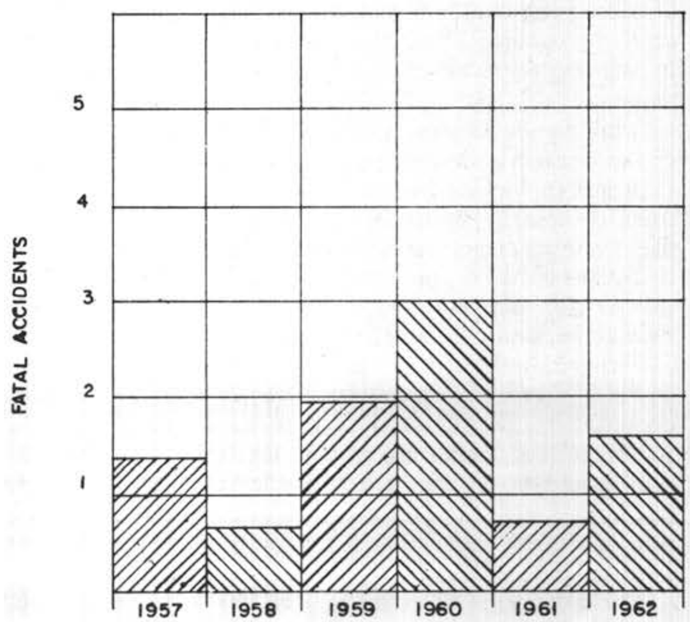


Figure 2

NUMBER OF FATAL ACCIDENTS PER MILLION MANHOURS WORKED IN URANIUM MINES

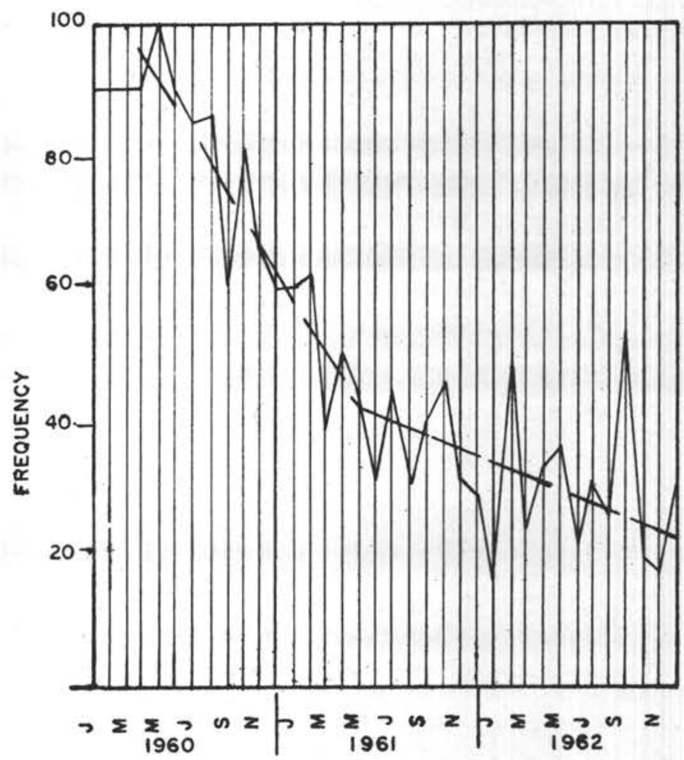


Figure 3

LOST-TIME ACCIDENTS PER MILLION MAN-HOURS (FREQUENCY) HAVE CONTINUED TO DECLINE SINCE FORMATION OF THE URANIUM OPERATORS SAFETY COUNCIL

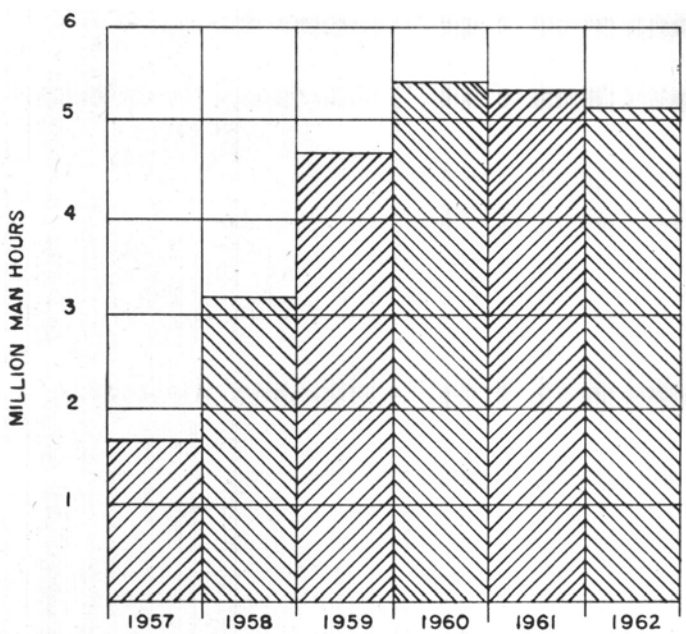


Figure 1

MILLION MANHOURS WORKED PER YEAR AT UNDERGROUND URANIUM MINES IN AMBROSIA LAKE AREA of safety personnel, have resulted in new safety rules and incentive programs. These also have had a tremendous effect in reducing accidents in addition to building up employees' morale.

A mine rescue station which comes under the jurisdiction of the council is situated in the center of the mining area. In it are 12 McCaa two-hour breathing apparatus and the usual equipment that constitutes a rescue station. To date, fifty employees from the various operations have been trained by Bureau of Mines personnel, and a detailed plan is in effect to cope with any eventuality. Refresher courses are given from time to time and the council now has its own instructor.

Recognition through the press and radio is given to mines and mills that achieve safety records established by their own organizations. Despite the adverse criticism given the area by the press, it is interesting to note that mines have worked several months without a lost-time accident and one mine has worked more than three years wtihout one. In 1961, one company in the area received the Award of Honor from the National Safety Council.

The cooperation of certain agencies has been advantageous to all the operators. The U.S. Bureau of Mines (which has no jurisdiction over the uranium mines in the Grants District) was asked by the council to conduct a study on roof control, which included testing of rock bolts in numerous mines. The Bureau accepted the offer and for six months its field engineers sought the answer to the roof-control problem.

Another problem confronting the council was the lack of safety training among mine supervisory personnel. The Bureau was again contacted and classes in accident prevention were held with 312 mine supervisors attending the courses and qualifying for the certificate. Similar courses were held for mine employees.

In all underground uranium mines, the control of radon and its daughter products is of the utmost importance. Although the State Department of Mines and Department of Health conduct periodic surveys, it is felt that additional training should be given to company engineers who are responsible for the frequent surveys needed for radiation control. The U.S. Department of Health in conjunction with the State Department of Health conducted courses for the personnel involved which resulted in better ventilation and

TABLE 1.

| PERIOD | MAN-HOURS WORKED | NO. OF OPERATORS REPORTING | NO. OF LOST-TIME ACCIDENTS | DAYS OF LOST TIME* | ACCIDENT FREQUENCY | ACCIDENT SEVERITY |
|---|---|---|---|---|---|---|
| *1960* | | | | | | |
| Jan.-April | 1,535,279 | 9 | 140 | 25,383 | 91 | 16,533 |
| May | 455,934 | 14 | 46 | 12,452 | 101 | 27,312 |
| June | 445,528 | 12 | 39 | 6,244 | 88 | 14,015 |
| July | 481,967 | 14 | 41 | 12,345 | 85 | 25,614 |
| Aug. | 527,774 | 14 | 45 | 24,710 | 87 | 47,921 |
| Sept. | 487,141 | 15 | 29 | 465 | 60 | 955 |
| Oct. | 493,590 | 15 | 39 | 12,423 | 81 | 25,700 |
| Nov. | 489,511 | 15 | 32 | 6,376 | 65 | 13,025 |
| Dec. | 509,861 | 15 | 30 | 6,302 | 59 | 12,360 |
| *1961* | | | | | | |
| Jan. | 487,824 | 16 | 29 | 6,319 | 59 | 12,953 |
| Feb. | 486,550 | 16 | 30 | 379 | 62 | 779 |
| March | 512,760 | 16 | 21 | 375 | 39 | 724 |
| April | 490,187 | 16 | 25 | 592 | 51 | 1,208 |
| May | 473,034 | 16 | 21 | 6,499 | 44 | 13,738 |
| June | 458,384 | 16 | 15 | 438 | 32 | 955 |
| July | 409,865 | 16 | 19 | 385 | 46 | 940 |
| Aug. | 342,565 | 16 | 11 | 223 | 32 | 651 |
| Sept. | 357,934 | 16 | 15 | 259 | 39 | 725 |
| Oct. | 439,875 | 16 | 21 | 12,478 | 46 | 28,290 |
| Nov. | 433,644 | 16 | 15 | 12,299 | 32 | 28,480 |
| Dec. | 428,064 | 16 | 12 | 268 | 28 | 626 |
| *1962* | | | | | | |
| Jan. | 463,712 | 15 | 7 | 216 | 15 | 466 |
| Feb. | 418,112 | 14 | 21 | 283 | 50 | 677 |
| March | 459,964 | 14 | 11 | 6,322 | 24 | 13,745 |
| April | 409,335 | 14 | 14 | 6,345 | 34 | 15,501 |
| May | 433,077 | 12 | 16 | 12,400 | 37 | 28,632 |
| June | 414,568 | 12 | 9 | 6,325 | 22 | 15,258 |
| July | 388,832 | 12 | 12 | 12,320 | 31 | 31,685 |
| Aug. | 462,711 | 13 | 12 | 488 | 26 | 1,055 |
| Sept. | 422,864 | 13 | 23 | 6,664 | 54 | 15,759 |
| Oct. | 450,521 | 12 | 9 | 634 | 20 | 1,403 |
| Nov. | 409,245 | 12 | 7 | 358 | 17 | 880 |
| Dec. | 385,584 | 12 | 13 | 471 | 34 | 1,222 |

*6000 days of lost time counted for each fatal accident in accordance with National Safety Council and American Standards Association standards.

reduced radiation hazards in the mines. Similar courses in radiation protection were held for mill personnel. All these courses were arranged through the council.

Although most of the larger companies are individual members of the National Safety Council, it was decided that the council should join as an independent member in order that the smaller operations could receive the benefits from that organization.

In conclusion, it is plainly evident that the formation of the Uranium Operators Safety Council was needed in the Grants district. Active membership support, good guidance, enforcement of rules, lack of complacency, and other factors have proved invaluable to all concerned and have helped make Ambrosia Lake a safe working area.

# *Rudiments of Uranium Ore Metallurgy*

DALE C. MATTHEWS

## INTRODUCTION

The success of a milling operation is primarily dependent upon the ore-supplying mines. Nonetheless, an ore is worth no more than its economic recoverable values.

A metallurgist in evaluating uranium ore amenability is concerned not only with the equivalent $U_30_8$ grade, but with grindability, chemical requirements, extractions, physical properties, and associated impurities.

Process details have purposely not been incorporated; neither have mechanical aspects regarding choice of milling machinery, abrasion or corrosion-resistant equipment nor summarized operational cost data been presented. This paper deals in generalities and is trusted to suffice for those functionally interested in uranium ores but not necessarily involved directly with their hydrometallurgical treatment.

## ORE GRINDING

As a rule, an ore needs to be ground finer for carbonate leaching than for acid leaching. Of course, this would not be the trend if the uranium minerals were not further exposed by subsequent acid decomposition of the cementing constituents. Refractoriness to ore grinding or mineral-freeing varies considerably, sometimes even within a given mine, because of gangue inconsistencies.

## ORE LEACHING

Fundamentally, there are but two lixiviants, sulfuric acid and sodium carbonate-bicarbonate, used commercially for leaching uranium ores. Acid and carbonate-consuming constituents of an ore must be economically evaluated along with relative percentages of uranium dissolution. Some ores are found nonamenable to either commercial lixiviant process because their uranium minerals are too resistant to dissolution. These refractory minerals are generally multiple oxides of uranium as complexed with silicon, columbium, and/or tantalum. There are ores that require no more heat than generated by acid reactions. This is not the case in alkaline leaching; hence, supplying heat is an economic factor of consideration. Nonetheless, leaching residence time versus degree of heat needs its optimum determined with either lixiviant.

The major chemical cost for acid leaching is generally the sulfuric acid itself, and for alkaline leaching is sodium carbonate or its equivalent in caustic or bicarbonate. Often the calcite-type minerals in an acid-leach ore are the major acid-consuming constituents, while the gypsum-type minerals are often the major carbonate-consuming constituents in an alkaline-leach ore. A metallurgist must cope with these nonmetallic calcium salts, as well as the clays, and is therefore aided by a knowledge of their mineralogical formulae. However, he is just as involved with the lixiviant-consuming metallic minerals and organics. Nonetheless, he is fundamentally concerned with determining the total acid or alkali consumed in leaching and needs to establish the acid or carbonate-bicarbonate concentration required for effective uranium mineral dissolutions. Notwithstanding uranium dissolution, techniques need be applied to limit solubilities of impurities that form fouling or even poisoning constituents in subsequent process phases. These might involve polythionates or dithionates, cobalt, molybdenum, silicon, thorium, titanium, zirconium, and others.

From an academic point of view, a metallurgist likes to know with what uranium minerals he is working; but hydrometallurgically, he need only establish their solubilities in response to oxidation, whether the uranium is in an oxidized, partially oxidized, or reduced form. Plus-four valent uranium minerals need oxidizing to six-valent to be readily soluble in either acid or alkaline solutions. Air, manganese dioxide, sodium chlorate, and potassium permanganate are the principal oxidants employed, although copper-ammonia complex, other catalysts, and absorbents are sometimes used.

## SOLIDS-FLUID SEPARATION

Methods of separating the leached solids from the resultant uranium-bearing solution need to be evaluated for each ore. Some ore pulps are quite amenable to either filtration or thickening with limited flocculant usage, whether acid or alkaline leached. Other leached pulps are not so responsive; hence, the utilization of the resin-in-pulp (RIP) process in which the slimes are retained in the uranium-bearing solution resultant from either acid or alkaline leaches.

The mechanical approach to take in removing leached solids from a uranium-bearing solution is largely dictated by the physical properties of the leached pulp. Many plants filter directly, a few countercurrent decant (CCD) in thickeners and then filter, some just CCD with the first thickener overflow going directly to columnar resin operations, some parallel classifier CCD circuits with thickener CCD circuits, some find it desirable to clarify thickener overflows prior to their subsequent extraction circuits, and all RIP plants and some other plants utilize hydraulic cyclones in conjunction with CCD rake, drag, or spiral classifiers.

## SOLUTION EXTRACTION

The two types of ionic uranium extractants employed commercially are the solid resin anion-exchangers and the liquid organic solvents, including the amine anion-exchangers which are liquid counterparts to solid resins. The selection of one type over another is not just a matter of personal choice if optimum results are to be attained. A considerable amount of investigation as to respective adaptabilities must be given to the impurities in the uranium-bearing solution.

## ELUTING, STRIPPING, AND/OR REJUVENATING

The system to be employed in removing uranyl cations or anionic complexes, foulants, or poisons from any extractant is selected with due consideration to chemical cost requirements, but just as important are the relationships to necessitated plant downtimes and chemical-physical degradation of the extract-ant. Each ore again presents an individual problem.

## PRECIPITATION

Choice of yellow-cake precipitants generally falls in line with resultant yellow-cake specifications or retreatment phases. Magnesia, ammonia, and caustic soda are the principal choices, but milk-of-lime and sulfuric acid are often incorporated.

## SPECIAL HEAT TREATING

The foregoing has dealt with the hydrometallurgy of the more common raw-leached uranium ores, but nonetheless is applicable to heat-treated ores. Most vanadium ores having uranium as a by-product are initially high-temperature salt-roasted. Lignites require burning in most instances before leaching, and other high-organic-bearing ores require a so-called bake or low-temperature roast to effect efficient uranium extraction. Also, some yellow-cake precipitates are heat-treated to upgrade their uranium concentration and make other finished product specifications.

## SOME ECONOMIC ASPECTS

Total investment for the 27 domestic (national) uranium ore processing mills having a designed capacity of 22,500 tons of ore a day is estimated at $145,320,000. One mill with a designed capacity of zoo tons of ore a day cost $1,500,000 to build, while another with a designed capacity of 33o0 tons of ore a day cost $16,000,000. An added observation is that chemical costs per ton of ore vary between $1 and $7 in these 27 domestic uranium ore processing mills.

In 1961, the domestic uranium production from hydrometallurgicallv processed ores was equivalent to nearly 17,400 tons of $U_3O_8$, having an approximate gross value of $300,000,000.

# Growth and Production

WARD E. BALLMER

The dramatic introduction of the atomic age to the world brought exciting changes to New Mexico. These were not all scientific in nature, although new laboratories and test centers unlike those ever witnessed before soon became a normal part of the State's scene.

With the critical development of atomic and nuclear studies came a need for basic raw materials to meet the ever-growing demand for radioactive elements. In the interests of national defense it was imperative that domestic sources of supply be achieved.

Through the Atomic Energy Commission, the U.S. Government offered generous bonuses for the discovery of uranium ore bodies capable of being mined and Defense Minerals Exploration Administration loans for the development of deposits and mines. This brought floods of prospectors, as well as persons new to the ranks of mining, to join geologists in the search for uranium. Based on earlier knowledge, much of the exploration activity was centered in the Colorado Plateau.

The first discovery of note in New Mexico was made in 195o by an Indian sheepherder at Haystack Butte, near Grants. His find triggered renewed enthusiasm in the area and in late 1951 another major find was made on the Laguna Indian reservation, east of Grants. By 1953, The Anaconda Company had completed its Bluewater limestone mill and by 1954 as many as 16 producers were shipping ore to the mill. In 1955, the subsurface Ambrosia Lake deposits were discovered northwest of Grants, and a great program of drilling by numerous operators with phenomenal success soon established New Mexico's leading position in uranium reserves. The state that gave birth to the atomic age was also to contribute mightily to its growth.

As mining and metallurgical advances were made and regular production of uranium oxide was achieved, the nation was transformed quite speedily from a "have not" country to one capable of supplying its own needs. Brakes were put on the discovery bonus program, new exploration was curtailed, and efforts were all turned toward production.

It would be untrue, of course, to imply that the geologist alone has been responsible for the tremendous strides made in developing the domestic uranium industry, but he played a strong supporting role. His continuing performance is equally essential to the further development of the industry.

Unlike many minerals, much of the uranium found in New Mexico is in small, irregular deposits situated at varying depths from the surface. Completely new problems in mining and in rock mechanics have been faced and overcome. The regular services of trained geologists have assumed more importance in the economic and safe development of these ore bodies than in perhaps any other mining activity. For in New Mexico's underground uranium mines, in particular, a faulty geological prognosis can spell immediate failure—both in the conservation of known reserves and in expected economic recovery by the operator. There is little margin available for error.

The successful mining of some 18 million tons of ore (Table 1) under the most trying circumstances during the past seven years speaks well for the technology and the entire industry. Greater production possibly could have been achieved if necessary, but production schedules were geared to needs of the Atomic Energy Commission, almost the sole market during this period.

TABLE 1. NEW MEXICO URANIUM ORE PRODUCTION

| YEAR | TONS OF ORE | VALUE (IN THOUSANDS) |
|---|---|---|
| 1956 | 1,105,000 | $ 24,086 |
| 1957 | 1,175,742 | 20,538 |
| 1958 | 1,888,499 | 32,264 |
| 1959 | 3,269,821 | 53,463 |
| 1960 | 3,793,494 | 61,827 |
| 1961 | 3,361,036 | 62,480 |
| 1962 | 3,472,000 | 65,448 |
| Totals | 18,065,597 | $320,106 |

Figures on the production of uranium oxide in the State are shown in Table 2. Data for the years 1958-61 inclusive were obtained from the Atomic Energy Commission. From 1959 on, the output is preponderantly from the Grants region.

TABLE 2. NEW MEXICO URANIUM OXIDE PRODUCTION

| CALENDAR YEAR | TONS OF $U_3O_8$ | VALUE (IN THOUSANDS) |
|---|---|---|
| 1958 | 3,604 | $ 65,811 |
| 1959 | 7,200 | 118,200 |
| 1960 | 7,759 | 125,146 |
| 1961 | 7,750 | 123,794 |
| 1962 | N.A. | 110,373* |
| Total | 26,313 | $543,324 |

* Unofficial

It should be mentioned that ore-value figures listed in Table 1 are also included in the value of the uranium oxide, in which form New Mexico's production is delivered to the Atomic Energy Commission representatives. Table 2 reflects the total value of mining and concentrating operations.

An over-all view of the growth of the domestic uranium mining and milling industry is shown in Table 3. It is to be

TABLE 3. U.S. DOMESTIC PRODUCTION OF URANIUM OXIDE

| FISCAL YEAR | TONS OF $U_3O_8$ (DOMESTIC) | VALUE (IN THOUSANDS) |
|---|---|---|
| 1943-1947 | 1,440 | $ 3,139 |
| 1948 | 110 | 1,571 |
| 1949 | 120 | 2,047 |
| 1950 | 320 | 5,709 |
| 1951 | 630 | 12,613 |
| 1952 | 830 | 18,575 |
| 1953 | 990 | 24,354 |
| 1954 | 1,450 | 35,525 |
| 1955 | 2,140 | 53,543 |
| 1956 | 4,200 | 97,692 |
| 1957 | 7,580 | 159,635 |
| 1958 | 10,250 | 196,185 |
| 1959 | 15,160 | 280,460 |
| 1960 | 16,567 | 293,236 |
| 1961 | 17,758 | 302,951 |
| Total | 79,545 | $1,487,235 |

noted that the Grants region has produced more than half the domestic production of $U_3O_8$ in the past five years.

The switchover from the "have not" category to a position of "have" can be seen easily in Table 3. During the twenty-year period of its existence, the uranium mining and milling industry has had only one major market—the Atomic Energy Commission.

Presently, the industry is going through its first major step in the transition from a one-market producer to that of competitive producer on the open markets. The speed with which this transfer can be made, of course, depends upon the rapidity with which other industries are adapted to utilize atomic power. It is commonly predicted that 1 o to I2 years will be required before commercial demand for uranium approaches the current government consumption.

There seems to be little doubt that commercial demand for versatile uranium will grow in succeeding years, but the mining industry is faced with the immediate problem of keeping its mines and concentrating plants in an operable condition while producing at a minimum survival level.

The role of the geologist under these circumstances takes on increased responsibility. The providing of exact information on each separate ore deposit, the minimum rate and manner in which these can be economically mined, and the development of additional reserves—all normal functions of the geologist—will largely determine which operations will survive the transitional period and which will fall by the wayside.

# Index


Abo Formation, 191
"Acid suite" of minerals, 81
Acoma sag (embayment), 19, 20, 177
*Adularia*, 40
Age of deposits, 157, 181, 200
Algal reefs, 151, 195
Alta mine, 28, 29, 30
Alteration, 15, 38-44, 72, 100, 148, 173, 194, 207
Ambrosia fault zone, 20-21, 197
Ambrosia Lake anticline, 60, 66, 69, 72, 195, 198
Ambrosia Lake area, frontispiece, 1, 4, 5, 11, 15, 17, 20, 38, 53-121, 185, 186, 189, 192
Ambrosia Lake Mine Rescue Station, 264
Ambrosia Lake trend, 55, 56, 69, 73, 108
American Association of Petroleum Geologists, 216
*Amphiboles*, 41
Anaconda Company, 1, 2, 3, 4, 154, 164, 167, 212, 270
*Anatase*, 23, 38, 39, 40, 41, 42, 193
*Andersonite*, 21, 23, 28, 29, 36, 80, 81
Andesite, 214
*Anhydrite*, 10, 11, 185
Animas Formation, 159
Ann Lee mine, 82, 88, 89, 90-101, 113
Apache tears, 214
*Apatite*, 41
Archuleta arch, 19
*Ardennite* (santafeite), 34, 35, 47
Argillite, 193
Argon, 210, 214, 216
Arkose, 14, 38, 44, 66, 82, 117, 189
Arroyo del Agua area, 136
Ash leach, 173, 202
  theory, 194
Asphaltic material, 96, 97
Asphaltite, 22, 47, 88, 96, 118, 134, 180, 198
*Astragalus*, 4, 122
Authigenic minerals, 22, 23, 27, 29, 32, 33, 34, 35, 36, 38, 39, 40, 42, 43, 44, 97
Autunite, 21, 23, 29, 30, 32, 33, 123, 170, 180

Baca Formation, 20
Bacteria, 164, 185
  anaerobic, 164, 183, 185, 190, 195
  *Desulfovibrio*, 183
*Barite*, 3, 21, 22, 23, 24, 26, 29, 30, 32, 33, 34, 35, 69, 72, 103, 129, 133, 140, 146, 147, 148, 180, 186, 187, 188, 189
  radioactive, 26, 88, 103, 200
Basalt, 158, 170, 175, 192, 205, 208, 211
*Bayleyite*, 21, 23, 28, 29, 80, 81
Beacon Hill mine, 126
Becenti mine, 35
*Becquerelite*, 170, 180
Bedding
  channel, 82, 122, 124, 167 (*see also* Ore bodies, Channels)
  cross, 13, 14, 15, 54, 82, 122, 167
*Bentonite*, 14, 82, 122, 195
*Beryl*, 210
Beta analyzer, 253
*Betauranotile*, 34, 35, 140
Big Draw fault, 20-21
Biogenic sulfur, 183
Bioherms, 150-154
Biostromes, 150
*Biotite*, 122
Black (brown) barren material, 23, 71, 88, 96, 97, 98, 100, 102, 104, 111, 113, 132, 189
Black Jack No. 1 mine, 26, 29, 45-48, 202
Black Jack No. 2 mine, 46, 49-52
Black Mesa basin, 19, 200
Blanding basin, 19
Bleaching, 17, 96, 129, 132, 133, 134, 165, 167
Blue Peak mine, 4, 28, 29, 30, 123-124
Bluewater fault, 20-21, 123, 202
Bluewater ground-water basin, 219
Bluewater mill, 1, 270
Bluff Sandstone Member, 6, 7, 12-14, 16, 53, 82, 157, 167, 205, 217
Boudinage, 92
Bone, 33, 88, 122, 180
Braided stream channels, 122
Breccia pipes (*see* Pipes)
Brookhaven National Laboratory, 214, 216
Brown-buff sandstone member, 13
Brushy Basin Member, 3, 7, 13, 14, 16, 17, 45, 49, 53, 60, 74-75, 86, 91, 106, 117, 157, 167, 173
Bucky No. 1 mine, 25, 29
Buff shale member, 13

*Calcite*, 21, 22, 23, 24, 25, 26, 32, 35, 36, 38, 40, 47, 55, 69, 72, 89, 97, 98, 103, 105, 113, 122, 133, 140, 146, 147, 170, 191
Calumet and Hecla, Inc., 2, 117, 131, 256
Carbon, 96, 117, 121, 123, 129, 131, 133, 134
Carbon dioxide, 140
Carbonaceous material, 17, 21, 22, 25, 26, 29, 35, 52, 78, 88, 96, 102, 103, 104, 111, 118, 119, 121, 123, 126, 134, 159, 160, 162, 165, 169, 179, 181, 185, 188, 189, 200
Carbonized material, 10, 15, 96, 98, 133
Carbon-uranium ratio, 96
Carmel Formation, 6, 7
*Carnotite*, 21, 23, 27, 28, 29, 30, 32, 34, 35, 36, 80, 81, 123, 140, 170
Cellulose, 198
Central basin, 19
Century Geophysical Corporation, 4, 222, 228, 247
Chaco slope, 19
*Chalcopyrite*, 32, 33, 34, 180
Chama sag, 19
Chavez Member, 13, 14
Chelate, 22
*Chert*, 54, 72
Chinle Formation, 6, 8, 157, 205, 220
*Chlorite*, 24, 38, 39, 41
Church Rock area, 1, 192, 202
Church Rock mine, 29, 35
Channels, 15, 86, 90, 106, 114, 154, 173
Cliffside mine, 17, 31, 82, 86, 87, 88, 89, 108-116, 129, 131
Climax Uranium Corporation, 167
*Clostritium nigrificans*, 183, 185
Coal, 17, 22, 24, 25, 28, 45, 80, 117, 119, 163, 164, 198
*Cobalt*, 268
Cobalt minerals, 31
*Cobaltite*, 32, 33
Coenoplase, 151
*Coffinite*, 21, 22, 23, 24, 26, 29, 31, 32, 33, 34, 35, 36, 43, 44, 47, 52, 71, 72, 80, 87, 96, 102, 129, 133, 159, 170, 179, 180, 187, 193
Colloids, 198
Colorado Plateau, 6, 14
Computer (*see* Digital computer)
Conglomerate, 12, 15, 17, 38, 54, 55, 82, 86, 91, 94, 98, 103, 105, 106, 122
Corals, 151
Coring (*see* Drilling)
*Corvusite*, 23, 33, 80, 81
*Covellite*, 32, 33
Cow Springs Sandstone, 11, 12, 13
Crackpot mine, 158, 163
Crevasse Canyon Formation, 108
*Cristobalite*, 210
*Cryptomelane*, 21, 23, 28, 29, 30, 34, 35
Cuchillo Arroyo, 11, 12, 15
Cumulo dome, 209
*Cuprosklodowskite*, 32, 33, 34, 35
Curtis Formation, 8, 10, 11, 136

Dakota Formation, 3, 4, 5, 7, 13, 15, 17, 35, 45, 51, 129, 167, 170, 205, 217
Dakota mine, 29
Dakota rim, frontispiece, 137
Dalco shaft, 147
Dalton Sandstone Member, 191
Davenport mine, 126
Daughter products, 129, 134, 200, 222, 266
Defense Minerals Exploration Administration, 270
Defiance uplift, 19
Devitrification, 194
Diabase, 4, 33, 157, 158, 161, 170, 188
Diagenesis, 109, 116, 139, 140, 143, 152, 193
Diamond No. 2 mine, 35, 200
Dikes, 4, 33, 158, 170, 173, 197, 211
Digital computer, 234-243
  programming, 237, 240
Dilco Coal Member, 108
Disconformity, 54, 65, 117, 118-121
Discovery, 3-5, 45, 60, 66, 82, 90, 117, 122, 123, 136, 167, 177, 244, 270
Dog mine, 4, 29, 126, 128
*Dolomite*, 32
*Doloresite*, 80, 81
Doris mine, 4, 31, 129, 130
Drilling, 3, 4, 5, 50, 82, 90, 102, 117, 149
  core, 3, 4, 167, 222
  fan, 247, 248, 249
  hole deviation, 230-232
  longhole, 3, 5, 245, 247, 253
  noncore, 4, 167
  percussion, 124
  rotary, 3, 124, 149
  shot-hole, 4, 82
  wagon, 3, 149
Dysart No. 1 mine, 4, 17, 24, 29, 60-65

Eh, 81, 131

East Grants Ridge, 205, 206, 211
Electric logging (*see* Logging)
Enrichment, 199, 201
Entrada Sandstone, 3, 6-9, 10, 11, 12, 13, 139, 143, 150, 152, 157, 205
ore in, 148, 163, 164, 167, 188
Silver's members, 8
Equilibrium (*see* Radiometric measurements)
Estimation of reserves, 234-243
Exploration, 3-5, 82, 90, 102, 108, 117, 149, 167, 222, 270
Eyeball mine, 154, 156

Faith mine, 139, 144, 145, 187
F-33 mine, 33, 209, 212
Farris Brothers Mining Company, 156
Faults, 20, 22, 65, 66, 69, 71, 72, 78, 87, 102, 106, 114, 116, 124, 131, 133, 134, 141, 159, 165, 189, 200, 201, 202
breccia, 47
dip-slip, 80, 86, 102, 123, 207
gouge, 47, 69, 111, 131, 177, 201
reverse, 111, 163
ring, 109, 111, 131, 163, 177, 187
strike-slip, 47, 102
*Feldspar,* 15, 27, 38, 39, 41, 42, 44, 49, 54, 72, 80, 88, 97, 113, 122, 167, 170, 193, 210
*microcline,* 40
*orthoclase,* 122
*plagioclase,* 22, 122, 211, 214, 216
*sanidine,* 38, 40, 41, 42, 193, 214, 216
*Ferroselite,* 21, 22, 23, 25, 29, 30, 38, 69, 89, 111
Flat Top mine, 147
Flea mine, 4, 126
Flow banding, 210
*Fluorite,* 3, 33, 34, 35, 129, 140, 147, 148, 191, 201
Folds, 3, 10, 19, 20, 66, 67, 86-87, 108, 123, 124, 133, 141-144, 146, 150, 152, 159, 160, 197
disharmonic, 141-144, 146, 147, 148
Four Corners Exploration Company, 131
Four Corners platform, 19
Fractures, 3, 69, 71, 96, 98, 102, 107, 108, 111, 114, 123, 126, 133, 134, 141, 148, 159, 197

*Galena,* 23, 32, 33, 34, 35, 180
Galls, 65, 66, 99
Gallup district, 1, 192
Gallup sag, 19
Gallup Sandstone, 45, 90, 108, 201
Gamma-ray log (*see* Logging)
*Garnet,* 41, 161, 210
Gas Hills district, Wyoming, 28, 185
Gastroliths, 122
Geiger counter, 4
Geobotanical explorations, 3, 122
Geological Society of America, 216
Geothermometry, 22
Gibson rim, 45
Glen Canyon Group, 6
Glorieta Sandstone, 219, 220
*Goethite,* 23, 25, 28, 81
Gossett mine, 126, 129
Gouge (*see* Faults)
Grade (*see* Ore)
Grade control (*see* Mining)
Granite, 122, 209
Granite leaching theory, 195
Grants district, 1, 8, 10, 11, 12, 21, 136-149, 150-156, 186, 187, 219-221
Grants Mesa, 214, 215, 216
Grants mineral belt, 1, 6, 14, 19, 21, 159, 164, 165, 192, 195, 202, 206
Grants Ridge, 205-213
*Grantsite,* 33, 34
Green *"pascoite,"* 21, 23, 29
Ground water, 131, 147, 148, 162, 164, 173, 189, 193, 196, 202, 217-221
aquifers, 217-218, 220-221
composition, 164, 217-218, 221
connate, 191
occurrence, 147, 217-221
meteoric, 191
pumping from mines, 220-221
specific capacities, 220
water table, 165, 201, 219, 244-245
yields, 217-218, 220-221
Guidebooks, 1
*Gummite,* 34, 35, 140, 146, 147
*Gypsum*
Todilto Formation, 10-11
mineral, 10, 11, 21, 23, 31, 35, 36, 72, 122, 187

*Haggite,* 21, 23, 24, 25, 29, 33, 34, 35
Happy Jack mine, 28
Haystack Butte, 3, 5, 12, 146
Haystack Mountain Development Company, 3, 152, 154, 156
Haystack syncline, 124
*Hematite,* 23, 27, 33, 34, 35, 69, 72, 88, 140, 146, 147
*Hewettite,* 34
History, 1, 3-5
Hogan mine, 29, 131-133, 135
Hogback No. 4 mine, 5
Homestake Mining Company, 45, 66
Homestake–Sapin Partners, 2, 22, 26, 30, 66, 67, 68, 186, 189, 219, 221
Horace Mesa, 20, 206
Hospah oil field, 200
Humates, 116, 121, 162, 164, 198, 199, 202
Humic acid, 41, 78, 195, 198, 199
Hydrocarbon, 88, 118
*Hydrogen-autunite,* 170
Hydrometallurgy (*see* Metallurgy)
*Hydromica,* 24
Hydrothermal, 3, 4, 42, 43, 44, 135, 141, 148, 173, 183, 185, 186, 191, 196, 203

Igneous action, 3, 134, 135, 158, 159, 170, 181, 185, 191, 193, 196, 197, 200, 203, 205
*Illite,* 39
*Ilmenite,* 38, 41, 42, 193
*Ilsemannite,* 21, 23, 29, 36, 38, 47, 69, 88, 102, 113, 129, 135
Infrared absorption spectrogram, 198
Isotopes (*see* Sulfur isotopes)
oxygen, 189
sulfur, 182-190, 193

Jackpile mine, 1, 4, 11, 15, 17, 33, 158, 159, 160, 161, 162, 163, 164, 167-176, 186, 188, 192, 217-218
Jackpile sandstone, 7, 15, 16, 17, 31, 33, 35, 38, 157, 159, 160, 167, 177, 217
*Jarosite,* 35, 36, 180
*Johannite,* 180
Joints (*see* Fractures)
*Jordisite,* 21, 22, 23, 25, 29, 38, 69, 88, 102, 111, 113, 129, 133, 135
Junction Creek Sandstone, 12
Jurassic
faults, 86, 87, 159, 165
folds, 86, 87, 91, 129, 159, 162, 163, 167, 170
mineralization, 116, 157, 164
overlap, 14
pipes, 162, 177-181
slumping 159, 170, 177

Kaolin, 15, 17, 21, 24, 26, 27, 38, 39, 41, 42, 43, 54, 72, 88, 89, 97, 98, 100, 103, 113, 122, 165, 167, 170, 189, 193
Kerogen, 118, 134, 198
Kermac Nuclear Fuels Corporation, 2, 69, 72, 73, 81, 186, 189, 220
Kerr McGee Oil Industries, 4
K.S.N. Mining Company, 2, 90, 129, 136

L-Bar Cattle Company, 167
L-Bar deposit, 171, 173, 174
La Jara Mesa, 209, 214, 215, 216
La Sal Mountains, 185
Laguna district, 1, 4, 6, 8, 10, 11, 12, 14, 15, 21, 136, 157-181, 187
Lamprophyre, 211
Landslides, 208, 209, 210
Laramide, 20, 123, 131, 134
Late Tertiary
diabase, 161
faults and folds, 161
Leaching, 3, 126, 131, 195, 196, 199, 201
Lead-isotope ratios, 172, 196
Lead-uranium isotopes, 196, 212
*Leucoxene,* 41
*Liebigite,* 21, 23, 28, 29, 34, 35
Leisegang rings, 113
Lignin, 198
Lignite, 194, 202, 269
*Limonite,* 26, 35, 36, 69, 88, 123
Lithophysae, 210
Lobo Canyon, 214, 215
Logging, 3, 222-233
electric, 3, 4, 74, 82, 88, 111, 138, 222
equipment, 222, 223, 224, 225
gamma, 82, 167, 222, 224, 237, 247
interpretation, 224, 228, 229, 240-241
logs, 226, 229
procedure, 224
probing, 4, 250-251
problems, 224, 227, 229-230
Logs (*see* Wood, Ore bodies)
Lothman, Louis, 4
Lucero uplift, 19, 123, 159

Magmatic sulfur, 183
*Magnetite,* 38, 41, 42, 193, 211
Malpais mine, 4, 126, 129, 135
Mancos Shale, 4, 17, 45, 90, 205, 217
Manganese, 30, 35, 88, 113, 140
Manganese oxides, 34, 35
*Marcasite,* 21, 23, 25, 26, 30, 31, 32, 33, 34, 35, 38, 39, 81, 118, 133, 179, 180, 186, 187, 188, 189, 193
Mariano anticline, 47, 49
Martinez, Paddy, 1, 3
Marquez disconformity, 117, 118-121
Marquez mine, 4, 25, 26, 29, 30, 55, 117-121, 131, 256-263
Mary No. 1 mine, 29
McCartys sag, 200
McDermott Member, 159
Mesa Chivato, 20

Mesa Gigante, 12, 13, 15
Mesa Prieta, 20
Mesa Top mine, 4, 24, 29, 126
Mesaverde Group, 45, 207
Meseta Blanca Member, 191
*Meta-autunite,* 21, 23, 28, 29, 30, 32, 33, 35, 36, 170, 180
*Metahewettite,* 140
*Metatorbernite,* 170, 180
*Metatyuyamunite,* 21, 23, 27, 28, 29, 32, 33, 34, 35, 36, 80, 81, 170
Metallurgy, 268-269, 270
*Mica,* 41
Milling, 268-269
Mills, 1, 19-20, 270
Minerals, 1, 21-36
Mining, 1, 244-246, 270
  accidents, 264-266
  bulldozer, 3
  caving problems, 257-263
  development, 245-246, 247, 257
  dilution of ore, 253
  drainage, 244-245
  equipment, 244, 245, 246, 257
  grade control, 247-253
  heaving, 258
  history of, 244
  man-hours, 265-266
  methods, 60, 124, 147, 149, 178, 220, 245, 254, 255, 257, 261
  modes of entry, 45, 60, 72, 82, 90, 108, 117, 178, 244, 245, 256
  open-pit, 244
  operations, 72, 90, 117
  production, 60
  retreat, 257-259, 261
  rim stripping, 3
  roof bolting, 246
  safety, 264-267
  State Code, 265
  stoping methods, 245, 246, 247, 252, 254, 255, 264
  support, 245-246, 257-260
  trenching, 3
  ventilation, 245
  wet, 245-246
Mogollon highland, 13, 14, 173, 196, 197
Mogollon slope, 19
*Molybdenum,* 25, 36, 38, 60, 88, 97, 98, 100, 104, 111, 135, 170, 193, 268
*Montmorillonite,* 25, 39
*Montroseite,* 21, 22, 23, 24, 26, 29, 80, 88, 102, 111
Morrison Formation, 4, 6, 14-17, 53-54, 82, 90, 205, 217, 220
  Kelley and Wood's members, 12, 13
  Smith's members, 12, 13
Mount Taylor, 6, 19, 20, 158, 175, 191, 192, 193, 197, 200, 202, 205, 209, 212, 214

Nacimiento uplift, 19, 123, 159
National Safety Council, 266, 267
New Mexico State Engineer, 219
New Mexico State Inspector of Mines, 263, 264
*Novacekite,* 180
Nuclides, 182
Nutria monocline, 123

Obsidian, 72, 205, 209, 210, 214, 216
Oil
  dead, 123, 134, 136, 195, 198
  odor, 10, 136
*Olivine,* 211
Ore
  authigenic, 23, 32-42 (*see* Authigenic minerals)
  asphaltic (*see* Asphaltite)
  barren material (*see* Black barren material)
  banding, 99, 113, 180
  black, 24, 71
  bleached zones, 134
  carbonaceous, 22, 26
  gradations, 66
  grades, 4, 49, 60, 71, 72, 89, 96, 100, 104, 113 (moly), 114, 129, 144, 146, 148, 163, 170, 177, 222, 235, 237
  leached, 111, 126, 131
  mineral zoning, 81, 135, 149
  organic material, 22, 24, 80
  origin, 36, 54-55, 69-71, 72-78, 81, 100-101, 116, 119, 121, 126, 148, 157, 159, 162, 164-165, 172, 173, 181, 191-204
  oxidized, 21, 24, 27, 28, 33, 35, 66, 116, 123, 126, 129, 134, 146, 147
  processes, 191-204
  rare elements, 48
  reserves, 234-243
  sampling, 4, 247-255
  supergene, 140, 144, 148, 199, 201
  syngenetic, 185, 195
  unoxidized, 20, 31, 33, 35, 66, 114, 159
Ore bodies
  belts, 55, 57, 94
  boundaries, 5, 100, 103, 146
  channels, 94, 114, 124, 126, 129
  cones, 162
  controls, 49, 54, 99, 129, 131
  faulted, 22, 65
  fish hook, 49
  ground-water control, 66, 102, 121, 129, 131, 133, 135
  grouping, 55, 72, 87, 144, 146
  halos, 47, 55, 94, 98, 99, 100, 105, 111, 149, 201
  host-rock thickness, 129
  lenticular, 49, 107, 111
  logs, 14, 22, 24, 25, 28, 30, 31, 33, 72, 98, 100, 119, 121
  mineral zoning, 81
  oxidation fronts, 66, 69, 70, 129, 131
  pods, 47, 49, 92, 94, 104, 111, 113, 114, 117
  postfault, 22, 45, 54, 80, 126
  prefault, 22, 45, 54, 80, 114, 126
  redistributed, 54, 55, 66, 69, 71, 114, 124, 126, 129, 134
  rods, 161, 164
  rolls, 66, 69, 71, 92, 103, 201
  satellitic, 92, 105, 124, 129
  shapes, 47, 49, 54, 55, 60, 66, 69, 72, 78, 92, 113, 124, 126, 131, 133, 134, 144
  shingle pattern, 94
  shoestring, 47
  slump structures, 92, 94
  specific deposits of Todilto, 146-148
  stacks, 54, 66, 68, 69, 80, 81, 114, 124, 129, 133, 134, 159, 199, 200, 201, 249, 254, 255
  steps, 92
  stratigraphy of, 53-59, 65
  structural control, 47, 66-71, 72, 78, 86-87, 91-92, 102, 108-111, 114-116, 124, 129, 130, 131, 133, 134, 141, 143-144, 146, 147, 148, 150, 151, 163-164, 177, 199, 200
  trends, 50, 54, 55, 60, 66, 68, 69, 71, 72, 73, 80, 82, 85, 87, 88, 114, 199, 201, 248
  zones, 50, 52, 55, 56, 57, 60-65, 72, 87, 88, 103-106, 108, 113, 114, 126, 133, 135
Ore textures, 97, 99
  acicular, 24
  anhedral, 25
  bladed, 24, 25, 33
  blebs, 98, 114, 140
  botryoidal, 24, 26, 28, 31
  "bow-tie," 24
  cementive, 96
  colloform, 33
  concretionary, 89
  crusty, 24, 27, 28
  drusy, 26
  fibrous, 28, 31, 33
  fine-grained, 22, 25, 33
  "flowers," 39
  geodes, 39, 41, 44
  mottled, 26, 99, 100, 105
  nests, 27, 39, 54, 88, 97
  pincushion, 29
  pisolitic, 31, 98
  platy, 30
  poikiloblastic, 26
  prismatic, 25, 26
  rosettes, 33, 35
  scaly, 27
  spherulitic, 31
  subhedral, 25
  veinlets, 140, 147, 187
  vugs, 24
Organic matter, 24, 38, 43, 44, 78, 111, 134, 140, 150, 193, 196, 199, 269
  chelate, 22, 24
Ortiz surface, 158
Oxidized minerals, 21, 24, 27, 28, 31, 268
Oxygen isotopes, 189

Paguate mine, 1, 158, 161, 167, 170, 173, 174, 217-218
Paragenesis, 43, 44
*Paramontroseite,* 21, 23, 24, 29, 31, 32, 33, 34, 80, 88, 102, 111
*Pascoite,* 21, 23, 29, 30, 34, 35, 36, 80, 81, 88, 102 (*see also* Green *pascoite*)
*Pascoite-like,* 30
Perlite, 205, 209, 210, 211, 214, 216
Petoch Butte, 8, 12, 13, 14
Petrified wood (*see* Wood)
pH, 81, 100, 101, 195, 196, 197, 198, 199
Phillips Petroleum Company, 2, 4, 88, 186, 189, 220
Phosphates, 27, 28-30, 33
Phosphoria Formation, 148
*Phosphuranylite,* 32, 33, 170
Pierce Canyon Formation, 40
Piercements, 92, 94
Pigment, 1
Pipes, 12, 15, 20, 108-111, 158, 163, 185
  Cliffside, 109, 113, 116, 129
  Jackpile, 172, 173, 188, 197
  Laguna, 161, 197
  Paguate, 181
  Woodrow, 163, 170, 172, 173, 177-181, 185, 187, 193, 195
*Pitchblende,* 22, 24, 26, 33, 80, 140, 146, 147, 148, 179, 180
*Plagioclase* (*see* Feldspar)
Plant fragments, 17, 22
Plug, 158, 197, 208, 211, 212, 214

Point Lookout Sandstone, 191
Poison Canyon area, 4, 122-135
Poison Canyon mine, 24, 26, 28, 29, 30, 124-126
Poison Canyon sandstone, 4, 15, 16, 28, 49, 53, 87, 117, 122, 123, 126, 256
Poison Canyon trend, 4, 55, 56, 69, 117, 122-135, 201
Pony Express beds, 10, 11, 136
Potassium-argon ratio, 212, 214-216
Precambrian, 6, 205, 192, 209
Precipitation of ore, 198-199
Pre-Dakota deformation (*see* Jurassic)
Prefault deposits, 22
Prewitt Member, 13, 14, 53
Primary minerals, 126, 140
Probing (*see* Logging)
Production, 167, 269, 270-271
  U.S., 270
  value, 270
Propylite, 193
*Psilomelane,* 30, 34, 35, 113
Puerco fault belt, 19
Pumpkin Buttes, Wyoming, 173
Pumice tuff, 208, 214
*Pyrite,* 21, 22, 23, 25, 26, 27, 31, 32, 33, 34, 35, 36, 38, 39, 40, 41, 42, 54, 69, 72, 81, 88, 97, 100, 111, 113, 118, 122, 133, 140, 146, 147, 148, 159, 170, 179, 180, 187, 188, 189, 193
Pyroclastics, 41, 122, 193
*Pyroxene,* 41, 211
*Pyrrhotite,* 188

*Quartz,* 24, 25, 35, 38, 39, 40, 42, 43, 44, 49, 54, 72, 96, 97, 104, 148, 181, 191

Radioactive products, 129, 134
Radiogenetic lead, 196
Radiometric measurements, 4, 212, 224
  age, 212, 214
  beta analyzer, 253
  equilibrium, 126, 129, 134, 200, 202
  equipment, 4, 214, 222, 223, 224
  equivalent $U_3O_8$, 228, 229
  exploration, 3, 4
  gamma count, 60, 224
  Geiger counter, 4, 222
  interpretation, 229
  logging, 4, 222-233
  ratios, 212, 214
  scintillation, 167, 222
Radium, 126
Radon, 200, 266
Rare elements (*see* Ore)
*Rauvite,* 140
Recapture Member, 7, 13, 14, 15, 16, 17, 53, 54, 82, 90, 157, 167
  uranium in, 15
Red Bluff No. 8 claim, 151
Red Rock bench, 19
Reefs, 150-156
  forereef breccia, 150, 152, 153, 154
Resistivity (*see* Logging)
Rhyolite, 205, 209, 210, 214
Rialto mine, 29
Rimrock mine, 152, 155
Rio Cebolla area, 136
Rio de Oro mine (*see* Dysart No. 1), 87, 186, 187, 189
Rio Grande trough, 1, 6, 19, 20, 159, 202
*Roscoelite,* 31
*Rossite,*
*Rutile,* 41, 42

S. & A. Mining Company, 147
Sabre–Pinon Mining Division, 66
*Sabugalite,* 180
St. Anthony mine, 158, 162, 167, 170, 171, 173, 174, 186, 188
Salt Wash Member, 14
Sampling, 4
San Andres Formation, 219, 220
Sandstone mine, 82, 87, 88, 89, 102-107
Sandy mine, 10, 11, 158, 161, 186, 188
San Fidel anticline, 20
Sanidine (*see* Feldspar)
San Ignacio monocline, 158, 159
San Jose Formation, 20
San Juan Basin, 6, 11, 12, 14, 17, 19, 20, 45, 123, 136, 141, 150, 157, 158, 159, 177
San Juan Mountains, 10
San Mateo fault, 20-21, 87, 113, 123, 197, 200, 202
San Mateo mine, 29, 123
San Mateo mineral hiatus, 131
San Mateo syncline, 87, 123, 129, 131, 133, 135
San Rafael fault, 20-21, 86, 197, 198, 202, 205, 207, 211
San Rafael Group, 6, 12, 14, 220
San Rafael Swell, 6, 11
Sanostee area, 136
*Santafeite,* 34, 35
Santa Fe Pacific Railway Company, 3
Sapropel, 199
*Schroeckingerite,* 23, 28, 123
Scoria, 205, 211
Section 10 mine, 24, 29
Section 15 mine, 22, 24, 25, 26, 29, 30, 66, 69, 187
Section 17 mine, 29
Section 20 (Poison Canyon) mines, 126-127
Section 22 mine, 24, 26, 27, 28, 29, 80-81, 189
Section 23 mine, 26, 28, 29, 66, 68, 69, 189, 221
Section 24 mine, 24, 29
Section 25 mine, 29, 71, 221
Section 25 mine (Todilto), 152, 154
Section 28 mine, 29, 189
Section 30 mine, 26, 29, 72, 79, 189, 199
Section 32 mine, 29
Section 33 mine, 26, 29, 189
Section 34 mine, 29
Section 36 mine, 29
Sedimentary breccia, 152, 153, 154
*Selenium,* 4, 22, 25, 70, 98, 100, 102, 111, 122, 129, 170, 193
  gray, 21, 23, 29, 30, 60, 69, 89, 111, 118
  red, 21, 23, 29, 30, 35, 69, 89
*Sericite,* 193
Shards, 122
Shinarump Sandstone, 129
Shirley Basin, Wyoming, 185, 189
*Shoepite,* 170
Sichel subroutine, 234
Silicification, 28, 30, 31, 121, 122, 194
Silicon, 268
Sills, 158, 161, 170, 172, 188
Silver's Jurassic members, 8
Silver Spur mine, 5, 17
*Sincosite,* 31, 32
*Sklodowskite,* 34, 35, 140, 170
Slump features, 92, 94, 109, 131
Smith Lake area, 1, 15, 45, 49, 192, 202
*Soddyite,* 32, 33, 170

Sonsela sandstone bed, 191
Southern San Juan Basin mineral belt, 21, 159
*Sphalerite,* 32
State Department of Health, 266
Statistical analysis, calculations, 234, 241
Stratigraphy, 6-18, 45, 53-59, 82, 84, 85, 91, 102, 108, 122, 138-140, 150, 157, 167, 170, 177, 191, 193, 205, 217-218, 220-221
Structure (general), 6, 19-20, 45-47, 86-87, 122-123, 137, 159, 174, 193, 195, 197, 202
Sulfates, 27, 28
Sulfur isotopes, 182-190, 193
  biogenic, 183, 185
  magmatic, 183, 185
  sulfide, 183
Summerville Formation, 6, 7, 11-12, 129, 139, 143, 146, 148, 167, 205
  uranium in, 12
Supergene action, 135
Supergene minerals, 21, 30-31, 33, 35, 66, 71, 81, 126, 129, 134, 135, 140, 146, 147
Syngenetic, 4, 173, 195

Taffy mine, 29
*Thenardite,* 21, 23, 29, 31, 36, 88
Thermograms, 198
*Thermonatrite,* 21, 23, 29, 31
Thoreau homocline, 136, 141
Thoreau Member (Formation), 11, 12, 13
Thorium, 268
*Thucholite,* 198
Titania, 38, 39, 42
Titanium, 268
Titanium minerals, 27
Todilto Formation, 6, 7, 10-11, 12, 21, 53, 109, 124, 129, 131, 136-149, 150-156, 159, 164, 198, 205
  brecciation, 140, 142, 143, 153
  deposits of, 33, 144-148, 152, 186, 187
  gypsum, 11, 13, 136, 157
  Limestone, 1, 3, 33, 136, 157, 187
  crinkly, 10, 136, 137, 139, 142, 143, 144, 147, 149, 150, 205
  massive, 10, 136, 139, 150, 205
  platy, 10, 136, 137, 143, 144, 150, 205
  recrystallization, 137, 139, 140, 141, 142, 144, 148, 150, 152, 201
  reefs, 150-156
Todilto Park, 10
Todilto rim, 3
Todilto trend, 139, 140, 141, 148, 149, 192, 206
*Todorokite,* 21, 23, 24, 29, 30, 31
*Topaz,* 210
*Torbernite,* 180
Toreva Sandstone, 200
*Tourmaline,* 41
Trace elements, 48
Trash, 117, 119, 179
Trends (*see* Ore bodies)
Tres Hermanos Member, 170, 217
*Tridymite,* 210
Tuff, 122, 205, 208, 209
*Tyuyamunite,* 3, 21, 23, 26, 28, 29, 32, 33, 34, 35, 36, 80, 81, 87, 123, 140, 170

United Nuclear Corporation, 2, 45
U.S. Atomic Energy Commission, 1, 2, 4, 48, 156, 157, 182, 187, 212, 216, 229, 270, 271

U.S. Bureau of Mines, 266
U.S. Geological Survey, 1, 212, 219
U.S. Gypsum Company, 212, 216
*Uraninite,* 21, 22, 24, 29, 31, 32, 33, 34, 35, 36, 80, 140, 150, 159, 170, 179, 180, 188, 193
Uranium carbonates, 28, 111
Uranium Operators Safety Council, 264, 267
Uranium phosphates, 28-30
Uranium sulfates, 28, 111
Uranium vanadates, 27, 28, 140
Uranium-lead ratios, 212
Uranium-vanadium ratios, 88, 104, 111
Urano-organic complexes, 36, 116, 159, 191
*Uranophane,* 23, 32, 33, 34, 35, 36, 140, 170
*Uranopilite,* 21, 23, 28, 29, 32, 33, 180
Uravan mineral belt, 157
*Uvite,* 140

Valencies, 21, 24, 33, 80, 81, 126, 159, 268
Vanadates, 27, 33, 111
Vanadium, 21, 22, 24, 27, 36, 38, 52, 66, 69, 80, 81, 88, 98, 100, 104, 111, 126, 135, 161, 164, 170, 177, 193, 269
Vanadium clay, 31, 33, 34, 35, 159
Variegated shale member, 13, 14
V.C.A. mine, 29
Vegetal matter, 78, 159
Vitrain, 198
Volcanic activity, 3, 134, 148, 191, 192, 194, 197, 202, 205, 209, 212
Volcanic debris, 41, 122, 173, 203

Wanakah Formation, 10, 11, 12, 136
Weathering, 41
West Grants Ridge, 205, 206
West Ranch area, 192
Westvaco mine, 220
Westwater Canyon Member, 3, 4, 13, 14, 15, 16, 22, 38, 45, 54, 60, 72, 82, 90, 157, 167, 185
  units of, 16, 50, 52, 57-59, 64, 74, 75, 76, 86, 108
White sandstone member, 13
Wind River Formation, 198
Wingate Formation, 6, 7-9, 13
Wood, 14, 22, 24, 25, 28, 30, 31, 33, 72, 88, 98, 117, 118, 119, 122, 133
Woodrow mine, 31, 33, 158, 167, 170, 171, 173, 177-181, 185, 186, 188
Woodrow pipe, 31, 35, 129, 177-181
*Wurtzite,* 32, 33

*Zellerite,* 21, 23, 28, 29
Zia mine, 10
*Zippeite,* 21, 23, 28, 29, 32, 33, 36, 87, 102, 180
*Zippeite-like,* 21, 23, 28, 29, 32, 33, 35
*Zircon,* 41
Zirconium, 268
Zones (*see* Ore bodies)
Zuni centers, 6
Zuni fault, 123
Zuni highland (*see* Mogollon highlands), 122, 134
Zuni Mountains, 20, 148, 191, 192, 202, 220
Zuni uplift, 6, 19, 20, 122, 123, 140, 141, 143, 148, 191, 193, 196, 202, 205
Zuni volcanic field, 6

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