CIRCULAR 101

Exploration for Mineral Resources

Compiled and edited by
FRANK E. KOTTLOWSKI and ROY W. FOSTER

STATE BUREAU OF MINES AND MINERAL RESOURCES NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY
CAMPUS STATION SOCORRO, NEW MEXICO

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Summaries of technical talks presented at New Mexico Tech's Fourth Annual Idea Conference
May 2 and 3, 1968

Sponsored by the New Mexico Bureau of Mines and Mineral Resources and the New Mexico Tech Research Foundation

June 1969

STATE BUREAU OF MINES AND MINERAL RESOURCES NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY
CAMPUS STATION **SOCORRO, NEW MEXICO**

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GeoScience Research is the Key to Industrial Development

Contents

Preface

In Mexico, the official agency that aids in exploration for and development of mineral resources (except for petroleum) is called El Consejo de Recursos Naturales no Renovables— *The National Council of Nonrenewable Minerals*. This is a realistic title. When a pound of potash, copper, or uranium or a barrel of oil is produced, it is gone; it is not renewable. To keep New Mexico's mineral production high, to keep the Southwest's mineral production high, requires constant and increasing exploration and development. Thus the suggestion by Roy Foster in late November 1967 of the theme for New Mexico Tech's Fourth Idea Conference: Exploration for and Development of Mineral Resources.

Of course, this allowed us exercise of an altruistic motive as well, that of subtly showing the role that state mineral resources agencies, our own in particular, play in aiding in the discovery and development of mineral resources.

The plan of our Idea Conference of Mineral Resources Discovery and Development was simple, direct, and comprehensive. We were fortunate in having some of the nation's foremost explorationists tell us about new methods of exploration and about new uses for the time-tested, older methods. The speakers represented all organizations involved in exploration, petroleum companies, mining companies, geophysical companies, state geological surveys, the U.S. Geological Survey, and colleges.

Frank Simons described the total geoscience approach of the U.S. Geological Survey in its exploration for the critical heavy metals, especially gold. Larry Werts, Kerr—McGee Corporation, gave New Mexico's position in mineral production and present mineral exploration. Douglas Cook, Humble Oil & Refining Company, described the effective uses of exploration techniques for metals. Larry Rooney, Indiana Geological Survey, talked about facets of finding industrial minerals and rocks. Jim Malott, Continental Oil Company, elaborated on new ideas in petroleum exploration. George Keller, Colorado School of Mines, described techniques of geophysical exploration for deep ores. Homer Lawrence and Robert Baltosser, Birdwell Division of Seismograph Service Corporation, showed applications of their three-dimensional logging techniques.

Henry Birdseye, Albuquerque geologist, unveiled the possibilities of geothermal power in the Southwest. Howard McCarthy told about the use by the U.S. Geological Survey of mercury and other trace elements in geochemical exploration. Douglas Carter, U.S. Geological Survey and NASA, explained the applications of airborne and spaceborne remote sensors for mineral exploration. Alan Pope described and illustrated with moving pictures Sandia Corporation's terradynamic method of drilling test holes. George Griswold reviewed New Mexico Tech's explosives research, and Lamar Kempton directed a dynamic illustration of one of the projects with a blowdown tunnel demonstration at Tech's explosives test site. Max Willard led a geologic field trip, exhibiting the problems of ore finding, to the Luis Lopez mining district a few miles southwest of Socorro.

This circular contains some of the papers presented during the Conference. We hope they will prove of value to those who could not attend.

Frank E. Kottlowski
Roy W. Foster

Role of New Mexico Bureau of Mines and Mineral Resources in Discovery

by Frank E. Kottlowski

How important is the mineral industry to New Mexico?

During 1967, mineral production in New Mexico again reached an all-time high with a value of about $874 million, the largest for any state west of the Great Plains except California. And this despite six months of a copper labor strike and a 15 percent decrease in the value of potash produced! The mineral fuels—oil, gas, coal, helium, and carbon dioxide—totaled two thirds of this production. Nonmetals, chiefly potash, perlite, crushed stone, sand and gravel, limestone, and gypsum, made up 19 percent. The metal ores produced, mainly copper, uranium, molybdenum, and zinc, comprised 15 percent of the total mineral production. In comparison, the farming and ranching total income amounted to about $265 million, construction projects totaled about $380 million, and the tourist trade realized an estimated $110 million, all of which combined still total less than the minerals' contribution.

Taxes paid to the State of New Mexico and its taxing subdivisions by the mineral inudstry provided about $85 million in revenue, with almost $75 million coming from the petroleum industry alone. Adjoining southwestern states, Texas, Arizona, Colorado, Utah, and Nevada, show similar patterns of mineral production forming a large part of their economies.

The New Mexico Institute of Mining and Technology consists, by law and by order of its Board of Regents, of three divisions: The College Division, responsible for educating exploration scientists; the Research and Development Division, which carries out many basic scientific studies, including some concerning geophysics and hydrology; and the Bureau of Mines and Mineral Resources Division, the state agency required by law to aid in mineral exploration and development. It does this by providing clues to mineral resources discovery, either through its published reports or by individual exchanges of ideas and scientific information with explorationists, be they geologists, petroleum engineers, mining engineers, or independent prospectors. Thus, exploration personnel should visit with the Bureau staff, inspect Bureau facilities, peruse its technical reports, and, most important, discuss with its staff what the Bureau can do further to aid in mineral exploration and development.

One major problem is the diversity of New Mexico's mineral resources. A geologic guide to potash ore may be worthless in discovering uranium; the type of rocks that contain perlite almost never yield oil or gas. A clue to a rich copper deposit may be of no help in locating coal beds. Thus, study of only the principal minerals in the state requires a widespread, diverse, and costly research program. Since the state's high level of mineral production results in general from geologic exploration, research at the State Bureau of Mines and Mineral Resources is keyed to help such exploration.

The Bureau's present program is divided arbitrarily into five groups for study: metallic ores, industrial rocks and minerals, oil and gas exploration, geologic mapping, and basic research. Many of the projects overlap, of course.

Recent major studies of metallic ores have concerned the origin of red-bed copper ores in the Sacramento Mountains; the distribution of tin deposits in the Black Range; a statewide geologic survey of molybdenum deposits; and geochemical surveys of several mining districts. All these projects hope to uncover indications of hidden ore bodies, working from the known to the unknown.

Titaniferous sandstones in northwestern New Mexico; mineral deposits in Rio Arriba and other counties; a statewide study of zeolite occurrences; and a statewide investigation of expandable clays and shales comprise recent major studies of industrial rocks and minerals.

Major oil and gas exploration projects have examined the buried Pennsylvanian beds of southeastern New Mexico, where these strata are prolific producers of oil and gas; the sedimentary basins of south-central and southwestern New Mexico, which are similar to oil-producing basins of southeastern New Mexico; and the petroleum possibilities of Valencia and Socorro counties, as part of the Bureau's continuing county petroleum studies.

Geologic maps are basic tools in any exploration for mineral resources. The Bureau has endeavored to provide geologic maps of the Chama, Brazos Peak, Tierra Amarilla, and Ojo Caliente areas of northern New Mexico, the Luis Lopez area in central New Mexico, and the Walnut Wells, Carrizozo, and Las Cruces regions of southern New Mexico. These geologic maps cover about 2000 square miles.

Basic research projects have ranged widely. Key minerals, such as feldspars, mica, and silica, and carbonate minerals, like calcite, occur near ore zones. Bureau researchers hope to determine whether these minerals vary, even minutely, in direct relation to mineralization. Some of the landforms and Quaternary rocks of New Mexico under study include the sands, gravels, and clays, and even soils, you see almost everywhere. Although the sands and gravels are industrial rocks, some contain much underground water and nearly all of them serve to hide older rocks, thereby concealing ore deposits. If we can "technically" strip them away, we may reveal the hidden ores.

Similarly, some volcanic rocks contain mineral deposits, others do not. Examination of a geologic map of the state shows that about a third of New Mexico is underlain by volcanic rocks or volcanic sediments. Many metallic ores are related, in some known or unknown fashion, to igneous rocks that erupted from central volcanoes or along cracks in the earth. An intimate intertonguing of many different volcanic and associated sedimentary rocks resulted from these eruptions. In the region near Las Cruces, copper-lead-zinc-silver-gold mineralization occurred during the late stages of intrusion of a monzonite that crops out in the Organ and Dona Ana mountains. An upper rhyolite in the Dona Ana Mountains is postmineralization and, in places, covers ore bodies. Because we do not know the exact correlation of rhyolites from the Dona Ana Mountains westward to the Robledo—Uvas—La Mesa region, we do not know which volcanic units to the west might be mineralized and which rocks might be hiding ore deposits.

To solve this problem, the Bureau initiated potassium-argon dating of the main volcanic units, because by determining accurate ages of the preore and postore rocks, we can suggest areas where mineral deposits may lie buried. Actual discovery will be accomplished mainly by private companies, as it should be in our democratic society. At present, we have only two dates: the Uvas Basalt is 31 million years old and the first rhyolite beneath the Uvas Basalt is 33.6 million years old. Each date cost about $350 to obtain, so this research will proceed slowly. It could result, however, in the location of a multimillion-dollar ore body.

New Mexico's numerous hot springs, faults, and rhyolitic rocks provide a possibility of producing power from underground steam tapped by geothermal wells. The Bureau has taken the first step in this direction, namely, locating and studying regions of high geothermal potential.

Future basic geologic research will employ Tech's computer. For example, the Bureads essentially complete records for all oil and gas tests drilled in New Mexico can be stored on several small rolls of magnetic tape, and any part of this information can be retrieved by a simple computer program. Also with the computer, isopach and structure contour maps could be made that would considerably aid petroleum exploration.

Published results of projects in these five areas of study make pertinent information readily available to explorationists. The study of the San Andres Mountains, an 80-mile-long, north-south range in south-central New Mexico, provides one example. These mountains expose a very complete section of the rocks of the earth's crust, which range from a billion and a half years old to sediments deposited yesterday. These sedimentary rocks are the key to oil and gas exploration in south-central New Mexico. Four geologists with a crew of geology students measured and sampled 22,000 feet of rock strata, collected fossils, and mapped selected areas in the mountains. In the Bureau laboratories, the fossils were identified and rock samples were examined in detail under the microscope. The results of this investigation appeared as Memoir 1. A north-south cross section along the San Andres Mountains and adjoining ranges showed these factors related to oil and gas mineralization: (1) the northward pinching-out of the lower beds, (2) lenses of sandstone, chiefly in Virgilian rocks, and (3) reef limestones occurring particularly in the Virgilian sequence. Isopach maps compiled from this information showed other possible petroleum traps.

A 1956 geologic study by Bureau personnel of low-grade molybdenum ores near Questa preceded by at least five years development by the Molybdenum Corporation of America of its huge mine in the area where it currently extracts this ore. Results of the Bureau's study appeared in Bulletin 51. Bulletins 39 and 50 presented the results of geologic work in the Sacramento Mountains on late Pennsylvanian and early Permian reefs and described relationships of outcropping reefs similar to those that later produced oil and gas in southeast New Mexico. Various stratigraphic reports, mostly of outcropping sections of sedimentary beds, gave clues to the facies, source beds, and petroleum reservoir rocks in the subsurface of the state's productive areas, the southeast and northwest. Gypsum quarries in the state are now located in areas reported as especially favorable in the Bureau's Bulletin 68, and guides to the location of uranium ore bodies, as suggested in Memoir 15, may have helped explorationists find some of the numerous uranium deposits in the region north of the Zuni Mountains.

June 30, 1968, marked the end of the fortieth year of the New Mexico Bureau of Mines and Mineral Resources. In that time, the Bureau has published some 92 bulletins, 22 memoirs, 98 circulars, 8 ground-water reports, 78 geologic maps, 26 petroleum exploration maps, 6 resources and land status maps, 8 Scenic Trips to the Geologic Past guidebooks, 16 annual reports, 22 reprints of some of the more than 166 geologic articles originally published elsewhere, and numerous miscellaneous publications.

The New Mexico Bureau of Mines and Mineral Resources plays a vital role in mineral exploration and development in the state through its various programs of geologic study and research, its dissemination of pertinent and useful information, and its liaison work with geologists, engineers, prospectors, mining and petroleum companies, hydrologists, metallurgists, geochemists, geophysicists, and the general public.

Exploration Aspects of the U. S. Geological Survey's Heavy-Metals Program

by Frank S. Simons
U.S. Geological Survey,
Washington, D. C.

The heavy-metals program started in 1966 as a joint effort of the U.S. Geological Survey and the U.S. Bureau of Mines to stimulate national production of a group of metals that were in short supply from domestic sources. Some 8 or 9 metals were included in the beginning, but the emphasis since has been almost entirely on gold. U.S. Geological Survey Circular 560, published recently, summarized the results of the first 18 months' work. Therefore, I shall not review the entire program but shall discuss a few examples of the use we make of geology, geochemistry, geophysics, and various combinations of these in the search for exploration targets.

I should emphasize at the start that we are not in the business of finding ore deposits. Our intent is to carry our studies only to the point at which, in our judgment, an exploration target of possible interest to the mining industry has been identified. At the onset of the program, it seemed logical to concentrate the bulk of our field efforts, at least for the first few years, in areas already known to contain gold deposits. The projects discussed, with one exception, are therefore all in areas that have produced large amounts of gold, and, in one instance, silver.

The most productive gold mine in the United States by far has been the Homestake mine near Lead, South Dakota, with an output of perhaps 30 million ounces. The Homestake mine lies in a sequence of Precambrian metasedimentary and metavolcanic rocks, the so-called Lead sequence. The gold is concentrated in one of the lower units, the Homestake Formation of local usage. Ore occurs at or near the crest of a series of tight anticlinal folds plunging steeply southeast. Exploration of similar rocks in similar structural settings at several places southeast of Lead did not locate any significant gold deposits.

Our detailed mapping at and southeast of Lead during the past two summers has revealed the presence of volcanic rocks, formerly interpreted as intrusive, in the upper part of the Lead sequence. This discovery has, in turn, suggested that in the area south of Lead, rocks formerly believed to be part of the Homestake Formation may instead belong to the Flag Rock Formation of local usage, a volcanic unit younger than and separated from the Homestake by two other formations, in descending order, the Northwestern and Ellison of local usage.

The geologic structure is everywhere complex, and we have no assurance that this interpretation is correct; but, if it is, then possibilities exist for the occurrence of the Homestake Formation and, by inference, gold deposits at depth. The Survey plans a modest diamond-drilling program this summer to test these new stratigraphic and structural concepts. We arrived at these possibly significant reinterpretations mainly by geologic mapping, although considerable geochemical work supported by truck-mounted mobile analytical laboratories contributed.

Our restudy of the old bonanza gold camp of Goldfield, south of Tonapah in southwestern Nevada, began differently. Goldfield produced about 4.5 million ounces of gold and something like a million ounces of silver from an area about 1 mile square. The lure of these fabulously rich ores has ensured very thorough prospecting of the area since its discovery in 1902.

The rocks are almost entirely of Tertiary age, mainly highly altered rhyolitic volcanics. Given such a geologic setting and the extent of previous exploration, we thought that only a fairly sophisticated approach, possibly a study of patterns of rock alterations and trace-element distribution, might provide clues to the location of concealed ore deposits. Certainly, the likelihood that any outcropping gold deposits had been overlooked in that area was exceedingly remote. Accordingly, we made a mineralogical study of several hundred samples of altered rock, as well as a geochemical study of several thousand samples, but disappointingly, this work did not yield much information of immediate value. Rock alteration appears much the same in productive as well as nonproductive areas, and analysis of a large amount of geochemical data revealed no particularly suggestive anomalies.

However, detailed geologic mapping, carried out concurrently with the other work, began to point to the interesting possibility that the Goldfield district may form part of a volcanic caldera and that the fracture system along which the ore deposits formed might be part of or related to the system associated with the caldera. Evidence for the presence of a caldera at Goldfield includes (1) an arcuate band of silicified fractures defining an east-trending partial ellipse open to the east; (2) the occurrence of older rocks, both sedimentary and igneous, along the west edge of the district, as well as near the center of the area, where they may constitute a resurgent dome in the caldera—a rather common feature of calderas everywhere; and (3) numerous north-trending and east-dipping arcuate silicified fault zones downthrown toward the east. It is suggestive that the major ore shoots at Goldfield occurred along fractures dipping toward the center of the inferred caldera; the large production of gold came from the west side of this inferred

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* Publication authorized by the Director, U.S. Geological Survey.

caldera. Similar fractures might be expected along the rest of the caldera margin. We have planned diamond drilling to test this hypothesis along both the north and south rims this coming summer. Hopefully, such drilling will confirm the existence of inward-dipping, hence potentially ore-bearing, fractures.

About 150 miles north of Goldfield is Virginia City and the Comstock Lode. This district produced about $400 million in silver and gold (with a little more silver than gold) since its discovery in 1859, mainly from a 3-mile-long segment of the Comstock fault zone at and south of Virginia City. The Comstock fault, however, as a result of previous geologic mapping, was known to extend several miles farther to the north, and we thought that a careful study of this relatively unprospected part of the fault might reveal areas of rock alteration, geochemical anomalies, geologic structure, or some combination of these similar to the Virginia City segment.

During our study of the last two seasons, we have traced the Comstock fault fairly accurately for about 6 miles north of Virginia City. Rock alteration everywhere is so intense and trace-element distribution so erratic that we could recognize no geologic setting similar to that of Virginia City. In an effort to obtain more information than surface geology and geochemistry seemed able to supply, particularly on the nature of the alteration at depth, a series of IP and EM profiles was run, and an area found that shows an IP anomaly believed to be caused by sulfide minerals. This area is to be studied in detail this summer in an effort to discover the relationships among rock structure, rock alteration (both hypogene and supergene), geophysical characteristics, occurrence of sulfides, and the possible occurrences of precious metals. The problems at Comstock are very difficult, but we hope to have an answer to some of them in another year.

We pass now to a very different type of gold deposit. The Sierra Nevada has produced the bulk of California's gold output from lodes, recent placers, and fossil placers of Tertiary age. All these deposits have yielded a great deal of gold, but I wish to discuss only our work on the fossil placers. These deposits were worked on a huge scale by hydraulic methods until downstream silting caused damage to land and property, bringing about a court order that forced most operations to cease about 1884. In view of the large production and the likelihood of very substantial amounts of gold remaining in buried or otherwise undiscovered placers, modern studies of these deposits seemed justified.

Tertiary gravels of the Sierra Nevada lie in channels eroded when the mountain range did not exist in anything like its present form. The gravel source must have been far to the east of the present crest of the range, perhaps as far east as Nevada. After deposition, the gravels were buried by volcanic rocks and subsequently have been partly exhumed. The richest gold placers occur along the deepest parts of the channels and are associated locally with much secondary pyrite (the so-called "blue gravels") and with magnetite and other heavy minerals. If the placers are ever to be mined, these channels must be located as accurately as possible, even where hundreds of feet of volcanic rock may conceal the gravels.

Our studies have been aimed toward locating channels and have involved detailed surface mapping, followed with tests by geophysical methods to determine if any method or combination of methods can successfully delineate the gravel-bedrock interface and, if possible, recognize the gold-rich blue gravel. Geophysical methods included seismic refraction, magnetic, gravity, IP, EM, and resistivity. U.S. Geological Survey Circular 566 gives the results of these tests.

In brief, it seems feasible to determine location and configuration of channel bottoms by seismic methods, to recognize the blue gravel by EM supplemented by IP, to pick up concentrations of magnetite at considerable depth, and even to locate the deepest parts of the channels by gravity. The seismic method apparently can outline channel shape, even through a thick cover of volcanic rocks, but drilling will have to confirm this finding. Both the U.S. Geological Survey and the U.S. Bureau of Mines plan further geophysical tests, supplemented by drilling, to verify these results. The economic potential of these channel gravels is certainly problematic, but they unquestionably contain a great deal of gold, and its recovery poses an intriguing mining and metallurgical problem for the industry.

Heavy-metals studies so far discussed were land-based, but we also are doing considerable work in the near-shore continental shelf environment on the Atlantic, Pacific, and Gulf coasts, in the Bering Sea, and in the Gulf of Alaska. About one fifth of our heavy-metals effort is being expended in the marine field. These studies are only very preliminary; as you are aware, oceanographic work is extremely expensive, and with the limited funds at our disposal, we have had to concentrate our efforts in a very few places. I wish to discuss only one study area, the continental shelf of northern California and southern Oregon.

The Klamath Mountains of southwestern Oregon and northwestern California have produced about $100 million dollars in gold, with two thirds or more coming from placer deposits. Modern beaches along the adjoining coast have deposits of black sands containing gold, chromite, magnetite, and heavy minerals derived from sources in the mountains. Similar placer and beach deposits should occur on adjacent sea floors, and in an effort to find these, we began a series of oceanographic studies last year, in cooperation with the universities of California, Oregon State, and Oregon, to investigate the sea floor west of the Klamath Mountains. These studies included bottom sampling and shipborne acoustic-seismic profiling and magnetic measurements; they will be supplemented by airborne magnetic studies later this year. Several magnetic and geochemical anomalies have been found. Although the gold content in the surficial sediments on the ocean floor is low, it may reflect substantially higher concentrations beneath the recent sedimentary cover. Preliminary work shows that old channels can be detected, as well as heavy-minerals concentrations in these channels and in buried beaches. Whether or not economic concentrations may exist can be determined only by much more extensive sampling and drilling; some work along these lines is planned for this summer in co-operation with the U.S. Bureau of Mines.

Inasmuch as the topic of this symposium is exploration, I have emphasized field projects with exploration aspects. However, many projects in the heavy-metals program involve research on a wide variety of subjects. Some of these have already made significant contributions to our field studies, and we hope that most or all of them will ultimately increase our knowledge of ore deposits and enhance the probability of success in exploration campaigns everywhere. I will mention briefly a few that I believe of particular importance.

Prospecting for the platinum metals has been seriously handicapped by inability to detect and measure accurately small amounts of these metals. Two years of research by a sizable group of chemists and spectrographers has developed a combined chemical-spectrophotometric method that permits accurate and reproducible determinations of as little as 10 parts per billion of platinum or palladium in a 10-gram sample. The method, although complex, is now employed on a routine basis in Survey laboratories; U.S. Geological Survey Professional Paper 600-B contains the details. Another method, which uses a fire-assay preconcentration of the raw sample followed by spectrographic determination, has about the same sensitivity and is also in routine use in our Denver laboratory.

The emission spectrograph has been used for many years by the Survey and other laboratories for semiquantitative determination of 30 to 60 elements in rock, soil, and stream sediment samples. This method is rapid and economical, but we have had no simple way to compare and standardize results among various laboratories, instruments, and spectrographers, either our own or those of the commercial laboratories that occasionally work for us. Recently, we have had prepared five sets of glass reference standards containing five different concentrations of 45 elements and a matrix simulating that of a common silicate rock. We expect that these standards will alleviate the problem of interlaboratory variations in semiquantitative spectroscopy and consequently will improve the quality of our determinations.

The ability to detect trace amounts of gold and platinum is, of course, a basic requirement for a successful program in geochemical exploration for these metals. The problem of obtaining representative analyses of a sample of material containing relatively few particles of the mineral sought is a difficult one. The size of the sample analyzed is limited by analytical procedure and laboratory equipment available, and the detection limit of the analytical method is often higher than one would wish. Obviously, some simple method of concentrating the metals sought into a small fraction of the raw sample would proportionally increase the effective detection limit. The gold pan is a time-honored tool for accomplishing this end, and we have found it very useful.

However, other simple concentration methods also have been highly effective in certain environments. For example, in the black beach sands of Oregon and California, detailed studies have shown that practically all the gold is contained in the heavy, nonmagnetic fraction, less than about 0.12 millimeter in diameter. Thus, a simple screening to eliminate coarser material, followed by concentration of heavy minerals and removal of magnetic minerals, permits the making of much more accurate and reproducible analyses. This procedure has been checked repeatedly and has shortened very greatly the time needed to analyze the sample beach or marine sediments.

A principal aim of the heavy-metals program is to make the results of our investigations available to the public as soon as possible. We have elected to do so mainly through the medium of circulars, which may be obtained free from any Geological Survey Field Center or Public Inquiries Office. Circulars reporting results of the heavy-metals program are identified by a yellow, or perhaps I should say a gold, cover. To date, we have published about a dozen of these circulars, and we expect ten or fifteen more to come out within the next few months, including five or more on Alaska, where the program, because of the logistic peculiarities of work there, did not get into full swing until last summer. Some of the circulars have attracted little or no attention from industry so far, whereas others have stimulated appreciable activity, and one has led to the discovery and development of a significant gold deposit at Cortez, Nevada. We are also placing on open file many of the aeromagnetic maps prepared for the program. For Nevada alone, maps covering about 20,000 square miles have already appeared on open file at Reno and can be copied at cost.

In addition to the timely results reported in the circulars, we have in press two major publicatons, one on gold deposits in the United States and one on platinum deposits of the world. Both will appear as professional papers and are scheduled for release late this year or early next year.

The heavy-metals program is in a sense strongly mission-oriented in that it has concentrated largely on a single metal, gold. For such a program to be effective, we have felt that it should be broadly based on research encompassing the entire field of economic geology. Given this base, it follows that results applicable to mineral exploration in general should also eventually be forthcoming and that, in particular, exploration targets for almost any mineral commodity may turn up from time to time. An example of this is the recently announced discovery of very large, high-grade deposits of barite in East Northumberland Canyon north of Manhattan and south of Austin in the Toquima Range of Nevada. This discovery was made during a study of sedimentary facies in Paleozoic rocks of western Nevada as a possible clue to the location of gold deposits. Indeed, it may be that such by-products of basic research on ore deposits will prove the most important economic contribution of the program. In anticipation of these and other contributions, we ask for your continued support of this program.

Mineral Exploration in New Mexico

by Larry Werts
Kerr—McGee Corporation

The current status of mineral exploration in New Mexico might be the activity referred to by some people as the "triumph of hope over reality". But the gross value of mineral production in New Mexico during 1967, exclusive of of oil and gas, was 332.6 million dollars. The principal minerals produced were uranium, copper, molybdenum, coal, and potash with minor lead, zinc, and silver.

New Mexico's mineral production is not restricted to one section of the state but is rather generally distributed, with copper and associated molybdenum, lead, and zinc in the southwest, potash in the southeast, coal in the northwest and northeast, molybdenum in the north-central, and uranium in the northwest (fig. 1). Slightly more than one percent of the gross production value, or nearly 4 million dollars was spent on mineral exploration in New Mexico during 1967, principally in the search for uranium, copper, molybdenum, and coal. Most present mineral exploration is generally directed toward areas adjacent to known production.

COPPER

From 1963 through early 1966, the principal mineral exploration effort in New Mexico concerned copper and other base metals. Exploration activity was generally confined to the Basin and Range province of the southwest part of the state.

Currently, the most important copper deposit in New Mexico is the Chino mine of the Kennecott Copper Corporation at Santa Rita, which produces about 22,500 tons of ore a day having an average grade of 0.80 to 0.85 percent copper. Recently, the United States Smelting, Refining, & Mining Company announced initial production from its large replacement deposit of copper ore near Fierro, and Phelps—Dodge Corporation announced its intention to place its multimillion-ton porphyry copper deposit at Tyrone into production by mid-1969. These deposits are found in exposed "islands" of pre-Tertiary rocks that constitute less than 25 percent of the total land area in southwest New Mexico. The remaining 75 percent is covered by unknown thicknesses of Quaternary gravels or Tertiary volcanic rocks. Each of the three deposits was located by surface prospecting, geologic mapping, and subsequent exploration drilling.

In southwest New Mexico, as in southeast Arizona, there is a general feeling among many exploration geologists that a number of large porphyry and replacement copper deposits lie undiscovered in pediment or shelf areas where the pre-Tertiary rocks are covered by thin blankets of Quaternary gravels or Tertiary volcanic rocks. Much of the copper exploration effort in recent years in the two states has been devoted to determining the thickness of the overburden as well as searching for buried copper deposits. Various geophysical techniques have been used extensively because they offer a method of evaluating large tracts of land at minimum expense on a per-acre basis. Gravity and seismic surveys are frequently used to determine the overburden thickness, while electromagnetic, aeromagnetic, and induced potential surveys are used to detect the presence of mineralization. Induced potential, with its ability to detect the presence of disseminated sulphides, is now used extensively as a reconnaissance tool. Geochemical surveys are of little use in prospecting for deposits buried at depth, but they are often employed for prospecting in the pre-Tertiary rocks. Various remote-sensing techniques have been tested, but more experience is needed before applying them to mineral exploration.

The peak year for copper exploration in New Mexico was 1964, with more than twelve major mining and oil companies actively engaged in exploration for porphyry and tactite copper deposits in the New Mexico part (fig. 2) of the Basin and Range province. Among the most active were American Smelting & Refining Company, American Zinc, Anaconda, Bear Creek, Climax, Duval, Kerr—McGee, Miami, New Jersey Zinc, Phelps—Dodge, Phillips Petroleum, and Superior Oil.

The lack of success in prospecting the covered areas of New Mexico and Arizona indicates that geophysics alone will not provide sufficient information to thoroughly evaluate the potential for buried base-metal deposits. Without new ideas and new prospects, copper exploration in New Mexico sharply declined, until now only three major companies are engaged in copper exploration and these on only a limited scale and in a limited area.

URANIUM

Accompanying the decline in copper exploration in late 1965, a spectacular increase occurred in exploration activity for uranium. This is due to an increase in the forecast demand for uranium for nuclear power reactors.

Figure 3, from a recent speech by Dean A. McGee entitled *Energy—Past, Present, and Future*, illustrates the predicted increase in the demand for electrical energy

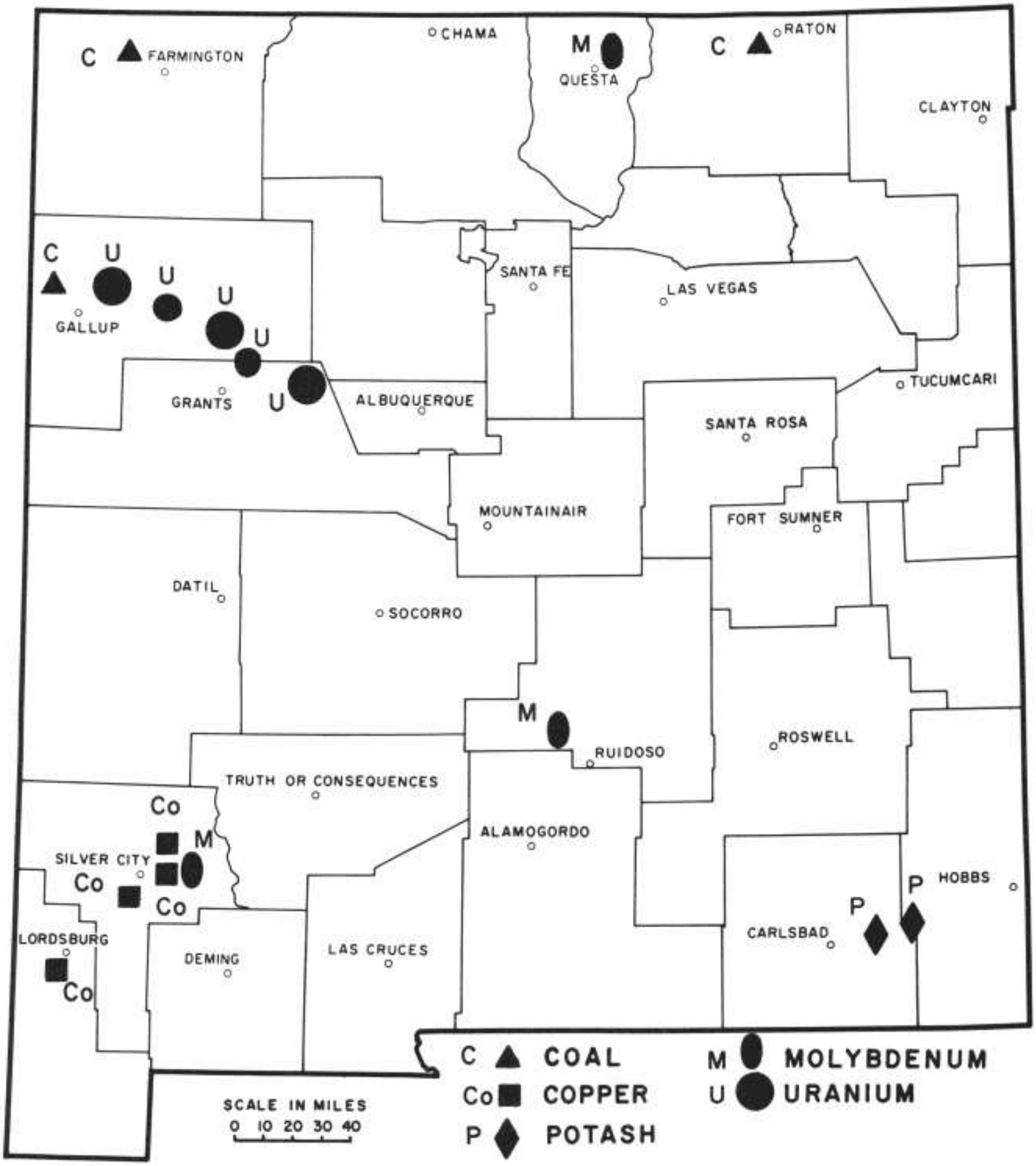


Figure 1
LOCATION OF PRINCIPAL NEW MEXICO MINERAL DEPOSITS AND PRODUCTION, 1968

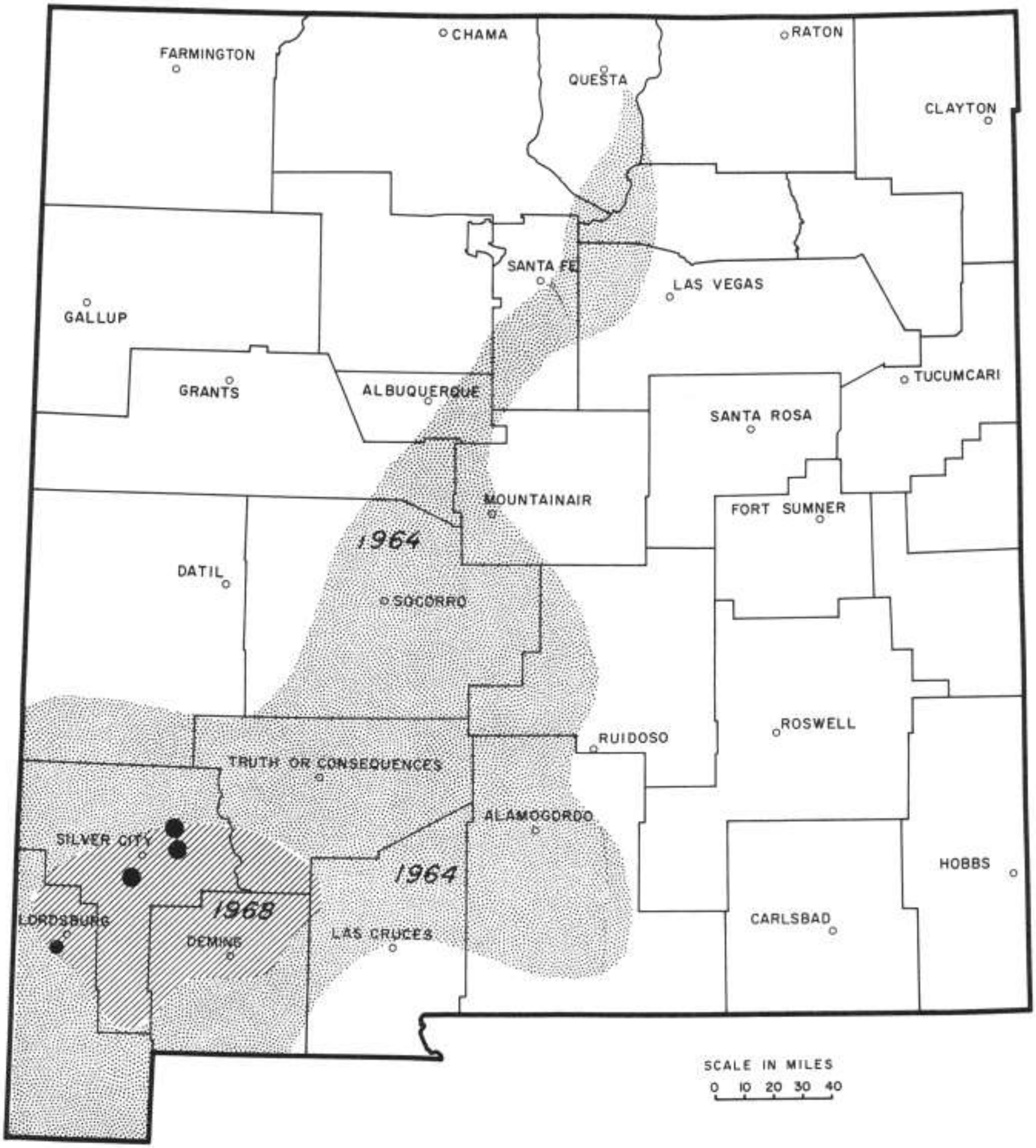


Figure 2
Copper exploration in New Mexico, 1968

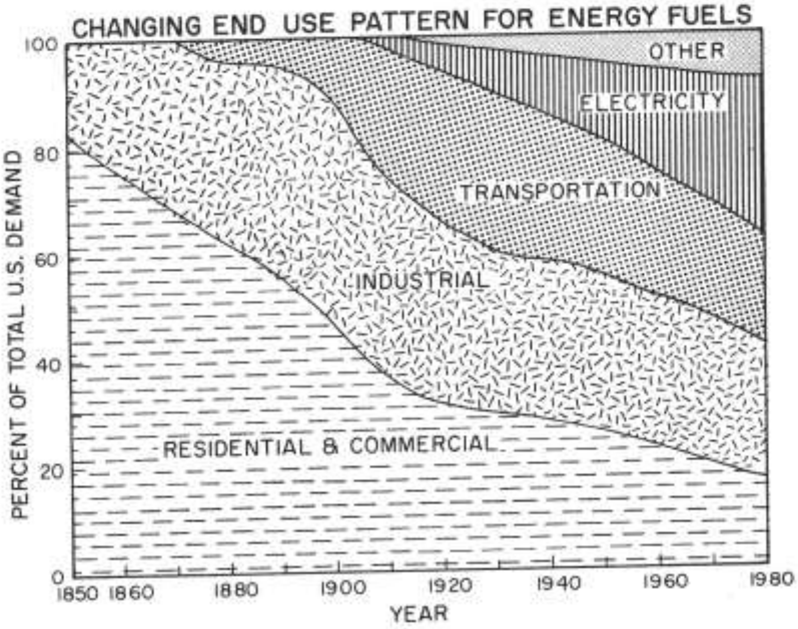


Figure 3
CHANGING END USE PATTERN FOR ENERGY FUELS

through 1980. The demand is shown to be doubling approximately every ten years, a growth rate roughly twice that of total energy.

Figure 4, from the same speech by McGee, shows the changing pattern of energy fuel demands for the United States' electrical power generation. Notice that the demand for uranium for use as a fuel in electric power generation increases dramatically through 1980 at the expense of other energy fuels. If you compare Figure 4 to Figure 3, you will realize that the growth in total electric power generation will be so great that an increase in demand for all energy fuels is forecast.

By January 1, 1968, a total of 88 nuclear power generation plants was operating, under construction, or planned in the United States. The Atomic Energy Commission estimates that nuclear electric power capacity will increase about 50 times over present capacity by 1980.

The best estimates (fig. 5) indicate that by the year 1980, total installed nuclear power capacity in the United States will be about 175,000 megawatts, or approximately 70 percent of the nation's present electrical generating capacity.

This translates into a growth in demand for uranium (fig. 6) for use in power reactors from 2000 tons in 1968 to 40,000 tons in 1980, or a forecast growth rate of nearly 30 percent a year. This figure is from a talk given by George C. Hardin at the A.A.P.G. 1968 technical sessions in which he mentioned that the forecasts themselves have also been increasing at the rate of 30 percent a year. At the present time, the United States' uranium industry has a producing capacity of about 15,000 tons a year. It is evident that this capacity must be more than doubled to meet the anticipated demand in 1980.

Nearly 42 percent of the nation's present uranium reserves are located in the Grants mineral belt of New Mexico.

The Grants mineral belt (fig. 7) extends from Laguna to Gallup and includes the Jackpile and Paguate deposits near Laguna, the Ambrosia Lake deposits, the Blackjack deposits near Smith Lake, and the Northeast Church Rock deposits northeast of Gallup.

Gross value of the uranium produced from the Grants mineral belt during the ten years prior to January 1, 1968, was about 4.06 billion dollars. Ultimate production from the district is estimated to exceed 2.5 billion dollars. By way of comparison, the Santa Rita open-pit copper mine was in operation approximately fifty years before producing 1 billion dollars in copper ore. By way of further comparison, the same gross dollar value could be expected from a 600-million-barrel oil field.

In January 1966, the Atomic Energy Commission reported that 94 percent of all United States' uranium production and ore reserves were found in bedded sedimentary deposits occurring in coarse-grained, continental, fluvial sediments. Similarly, uranium deposits in New Mexico occur principally in fluvioclastic sediments of the Jurassic Morrison Formation. Minor deposits occur in the Todilto Limestone, also of Jurassic age.

The radioactivity associated with uranium becomes an important exploration advantage over other minerals when radiation detection equipment is used to locate it. Uranium exploration in New Mexico has generally consisted of two types: (1) exploration for exposed deposits or those buried under shallow cover by airborne radiation surveys and (2) subsurface exploration in "favorable" areas where drill holes are logged with down-hole radiation detection equipment. The majority of the New Mexico deposits are buried at depths that prohibit airborne detection, so most present-day exploration is conducted in the subsurface.

In 1965, only two mining comapnies were actively exploring for uranium in northwestern New Mexico. By the end of 1967, more than twelve major mining and oil companies, together with numerous independent operators, were active in the same area (fig. 8). Currently active in the state are Anaconda, Atlantic—Richfield, Cities Service, Continental, Getty, Gulf, Homestake, Humble, Kaiser, Kerr—McGee, Ranchers Exploration, Sinclair, Sohio, United Nuclear, and Western Nuclear. During 1967, most of their efforts were concentrated in the northwest section of the state.

In the past three years, mining claims covering nearly 500,000 acres have been located for uranium in New Mexico. In the same period, uranium mining leases on state lands, averaging four sections a township, were acquired by various operators in the areas shown in Figure 9.

An average of 30 drill rigs was active in the state during 1967, with the result that footage drilled in uranium exploration rose from 722,000 in 1966 to 2,520,000 in 1967. An additional increase to 2.72 million feet is forecast for 1968 (fig. 10).

Uranium ore reserves in the Jackpile and Ambrosia Lake areas have been significantly increased as a result of recent drilling, and at least one large ore deposit has been discovered in the Northeast Church Rock area. United Nuclear Corporation is currently sinking an 1800-foot shaft on its Northeast Church Rock deposit.

At the present time, 35 drill rigs are active in uranium exploration in New Mexico, many of these operating on a 24-hour basis. Thirty-two of the rigs are located in the vicinity of known ore deposits along the Grants mineral belt, as shown by the gray dots on Figure 7. As the demand for uranium continues to increase, it is anticipated that much of the drilling activity will shift to testing new environments and developing new ore deposits outside the Grants mineral belt.

MOLYBDENUM

Molybdenum is produced in New Mexico as a byproduct at the Santa Rita mine of the Kennecott Copper Corporation and from an 11,000-ton-a-day open-pit mine operated by the Molybdenum Corporation of American near Questa. The Questa deposit is one of two in the United States currently being mined solely for molybdenum. Because of the rarity of large molybdenum deposits, explor-

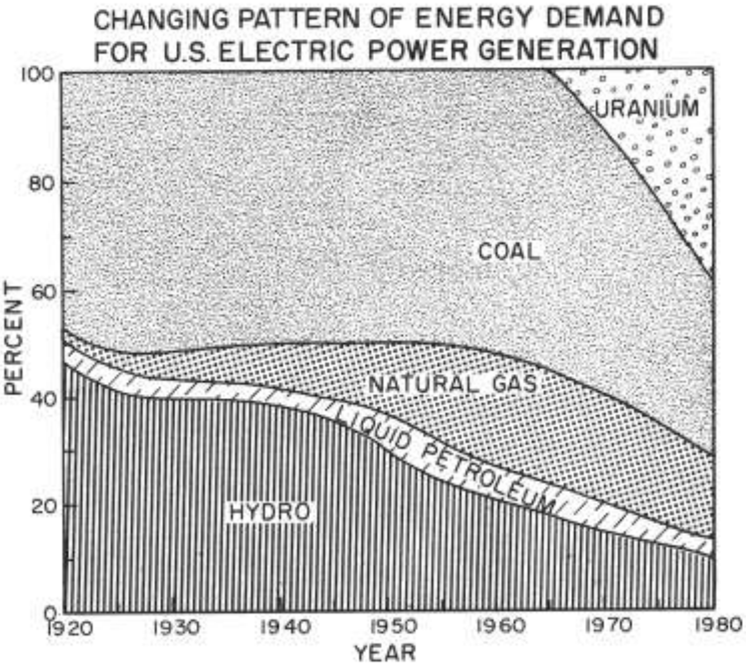


Figure 4
Changing pattern for energy demand for U.S. electric power generation

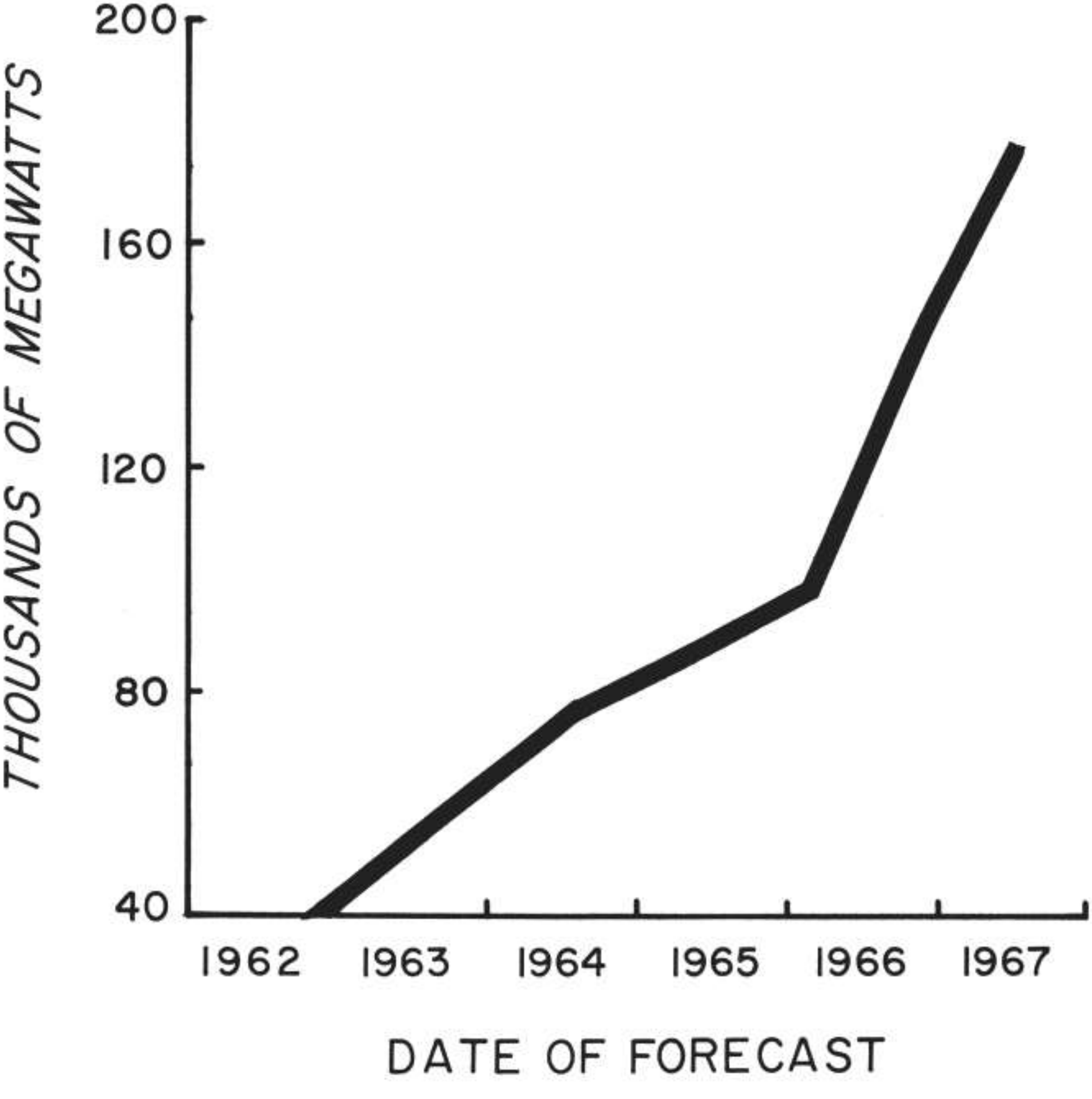


Figure 5
Forecasts of U.S. nuclear power generating capacity

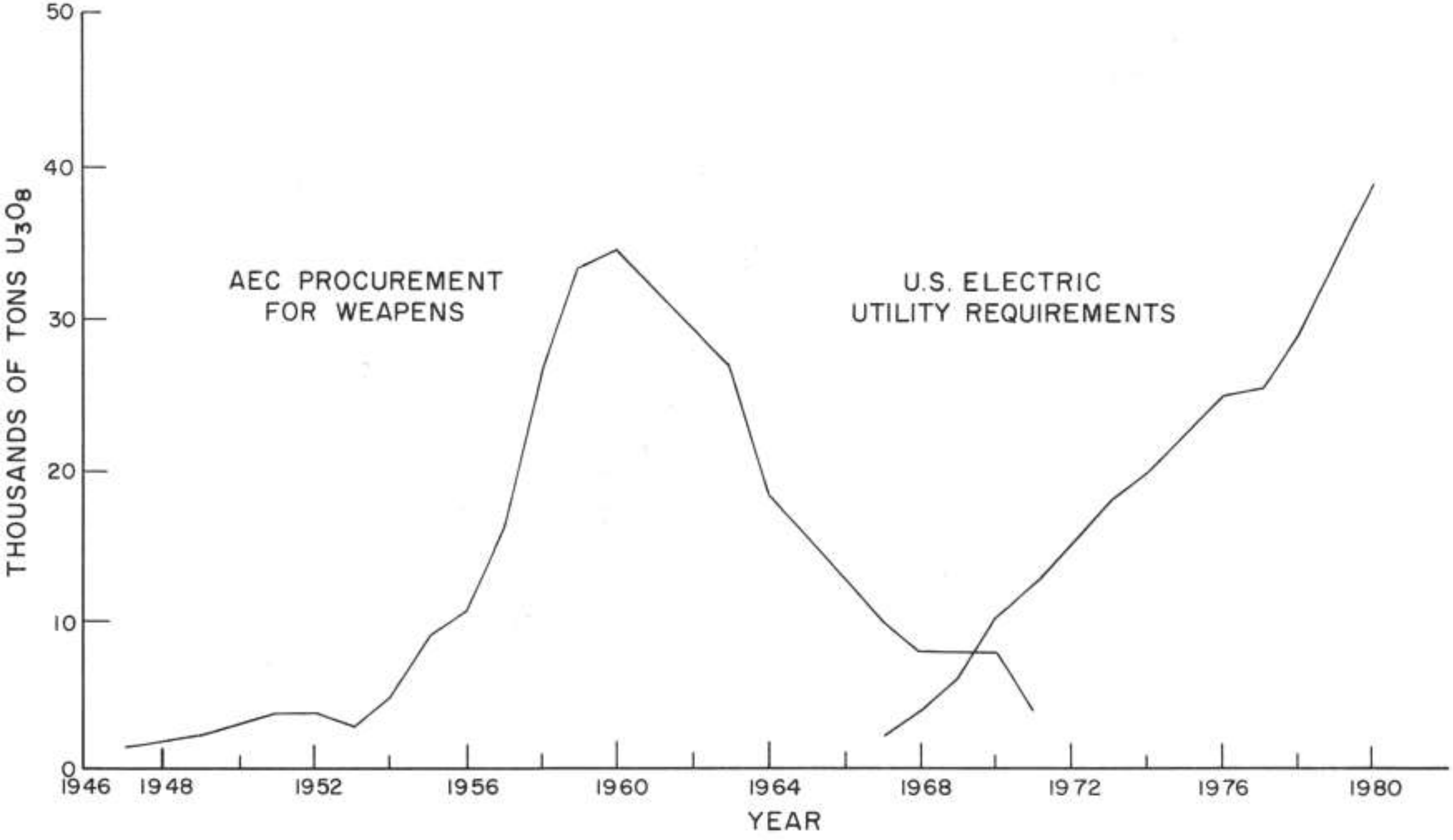


Figure 6
Domestic Uranium demand

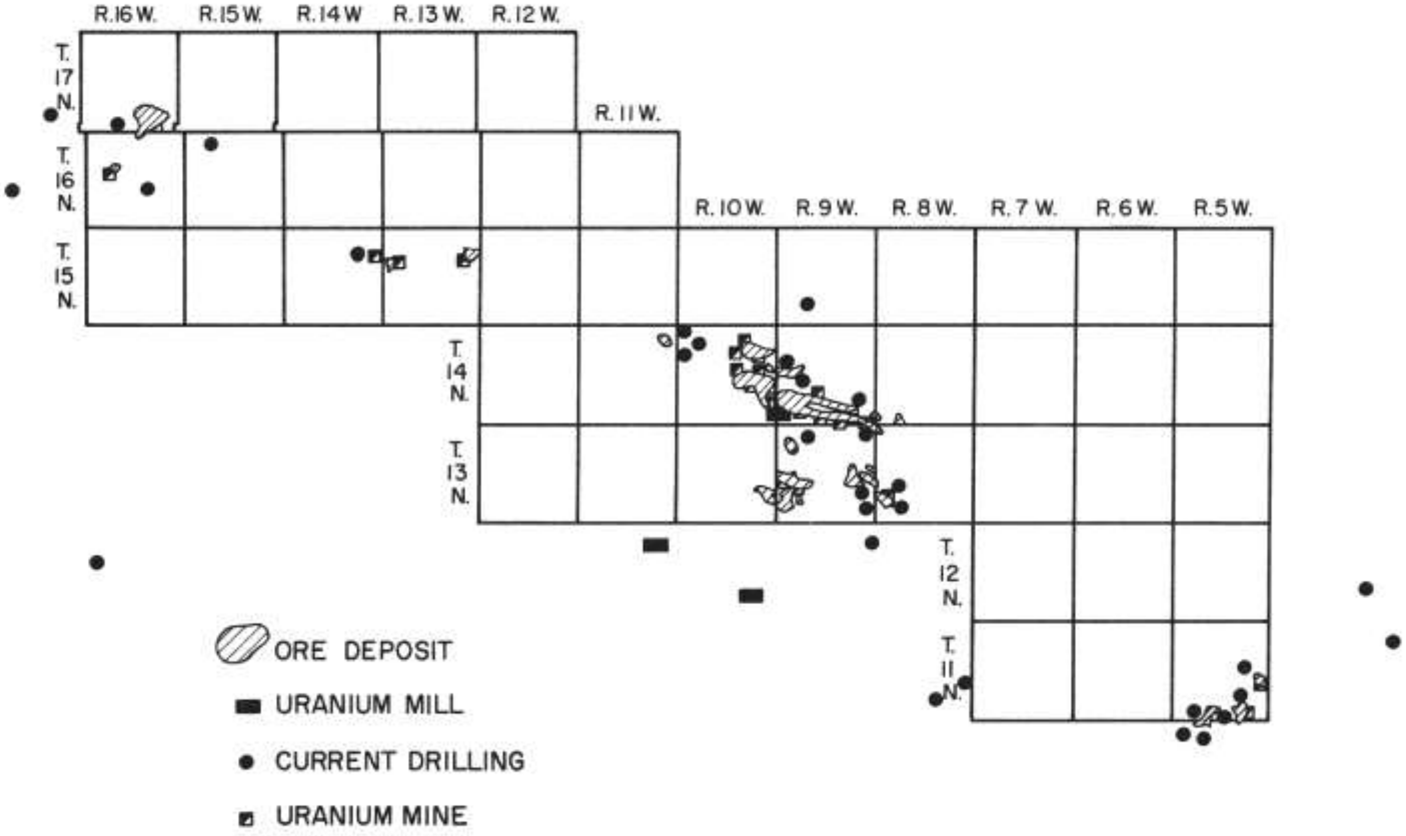


Figure 7
GRANTS MINERAL BELT

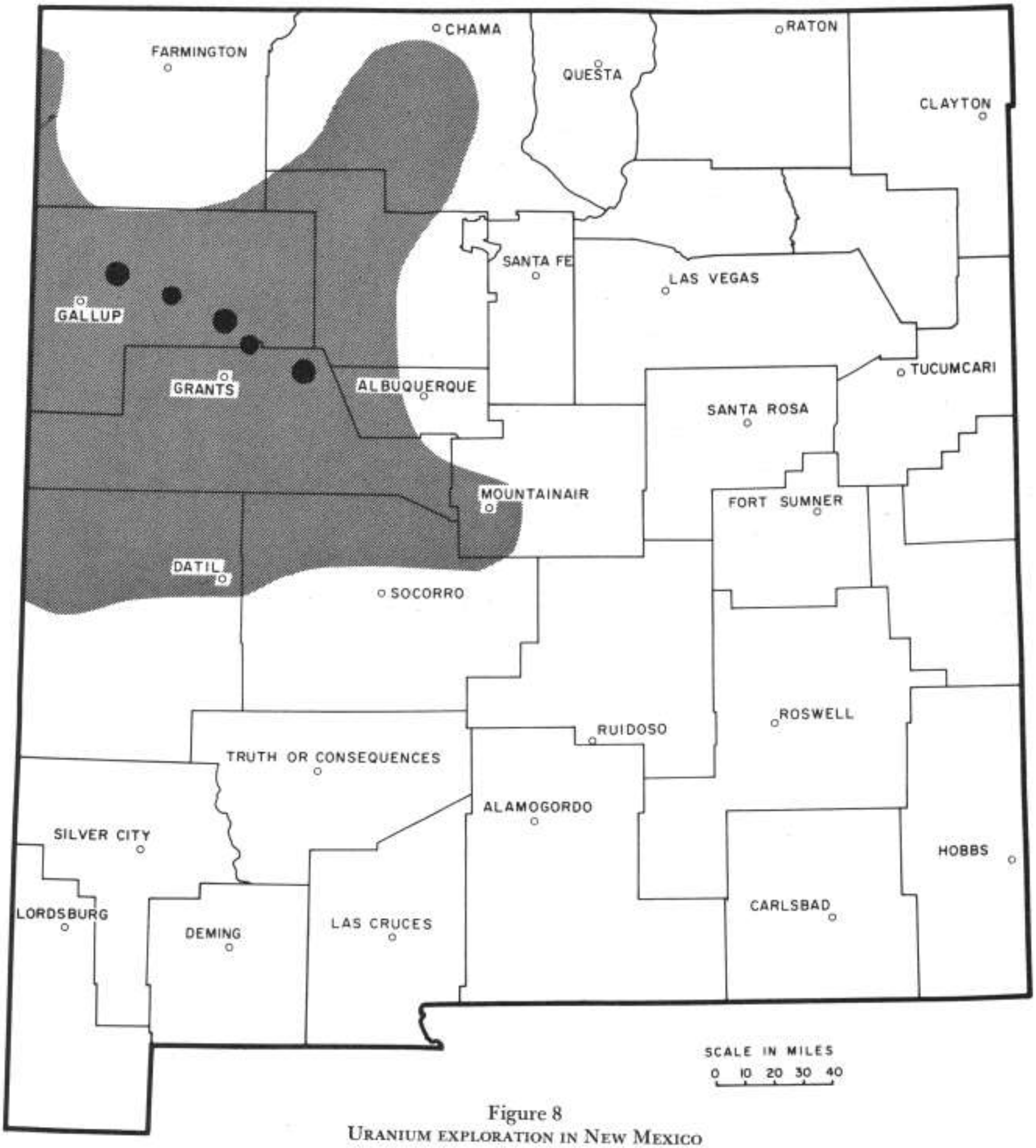


Figure 8
URANIUM EXPLORATION IN NEW MEXICO

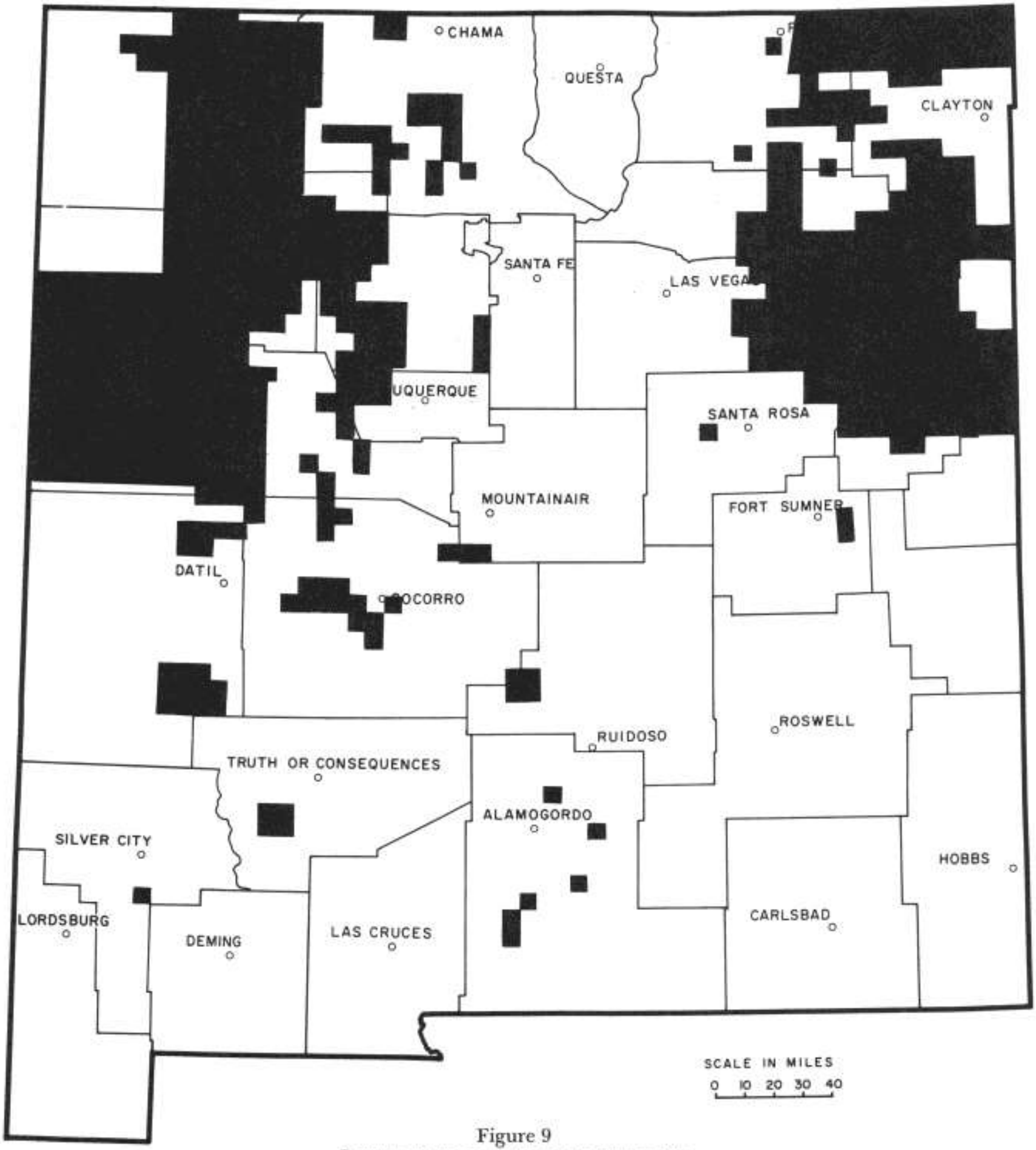


Figure 9
LEASED AREAS OF AVAILABLE STATE LAND

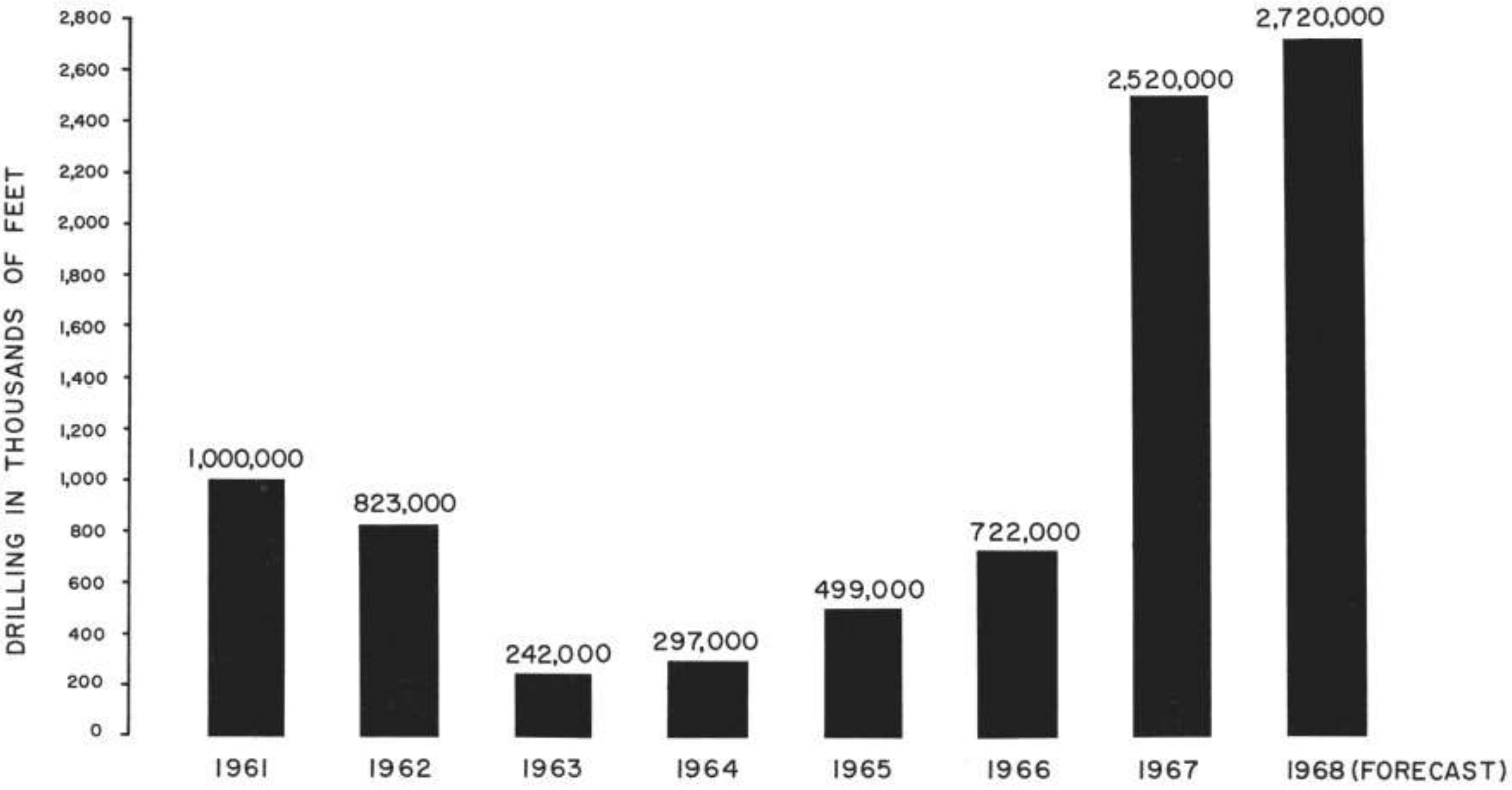


Figure 10
SURFACE DRILLING FOR URANIUM IN NEW MEXICO, 1961-1968

ation for molybdenum is usually conducted as part of a porphyry copper exploration program. The only prospect for a large, low-grade deposit of molybdenum now being tested in New Mexico is Bear Creek's Sierra Blanca prospect located near Ruidoso (fig. 11). Geochemical surveys, induced potential surveys, and limited drilling have been conducted on this prospect with encouraging results; additional drilling is planned.

COAL

Coal is one of the most important energy fuel sources in New Mexico, with deposits found at many locations, especially in the northwest quadrant (fig. 12). The U.S. Geological Survey has estimated New Mexico's coal reserves at approximately 62 billion tons, including 50.8 billion tons of subbituminous and 10.9 billion tons of bituminous, plus nearly 6 million tons of anthracite.

Coking coal is currently being mined by the Kaiser Steel Corporation from its York Canyon and Koehler mines near Raton; coal for out-of-state power is being produced by the Pittsburgh and Midway Coal Company from its open-pit mines 15 miles northwest of Gallup; and coal for the production of on-site power is being mined by the Utah Construction & Mining Company near Fruitland for the Arizona Public Service Company plant at the same location (fig. 13). Plant expansion is expected to require 8.5 million tons of coal a year from the Utah Construction operation. The Public Service Company of New Mexico has recently announced plans to establish a similar power plant in the area north of Fruitland.

Geology and exploration have never played an important part in the coal industry, principally because coal occurs as a stratigraphic unit and can easily be identified on outcrop. As a result, large reserves are usually developed with a few widely spaced holes. Currently, a great deal of attention is being given to coal as a source of synthetic hydrocarbon through liquefaction and gasification, for which the large, strippable coal deposits of New Mexico are almost ideally suited. As the demand for coal in the use of synthetic hydrocarbon manufacture increases, it is probable that the use of geology and more detailed exploration will also increase.

SULFUR

Sulfur is not presently produced in its raw form in New Mexico. However, numerous shows of sulfur have been reported in backreef and basin facies of upper Permian sediments of the Delaware basin in Chaves and Eddy counties fig. 14).

A boom in sulfur exploration is currently under way in Culberson County, Texas, and the activity has moved northward into western Eddy and southern Chaves counties, New Mexico. Sulfur leases have been acquired by Amerada, Atlantic—Richfield, Bear Creek, Duval Corporation, Phillips Petroleum, and Sinclair. Atlantic, Bear Creek, and Sinclair have drilled in the Carlsbad area and Duval has drilled near the town of Malaga. If substantial sulfur deposits are present in Chaves and Eddy counties, they will probably be discovered by intelligent subsurface analysis of data obtained from wide-spaced reconnaissance drilling and oil and gas tests rather than by accidental means.

The extensive gypsum deposits in southeastern New Mexico may offer a secondary source of sulfur if a process currently being developed by the Elcor Corporation at a plant in Culberson County is successful.

POTASH

Potash is produced in southeast New Mexico by Duval, Southwest Potash, Kerr—McGee, IMC, National Potash, and Potash Company of America (fig. 15). Because of declining market conditions, the dollar value of potash production in southeast New Mexico has decreased steadily for the past two years, even though gross output has remained almost constant. As a result, exploration for potash in the state has been almost entirely curtailed. Very limited exploration for langbeinite ores is being conducted in very select areas.

CONCLUSIONS

Uranium and copper are the most important metallic minerals produced in New Mexico. Substantial increases in the reserves of both minerals are required if projected consumer demands are to be met. To conduct the large-scale exploration necessary to meet such increased demands, exploration geologists working in New Mexico will be required to abandon their sometimes traditional roles as prospectors in favor of a more scientific approach. The temptation toward overreliance on electronic aids, such as induced potential surveys and remote sensing, should be tempered in favor of using these with other methods as tools of the over-all exploration program. Considerable effort must be spent in analyzing the geologic environment of known deposits. The information and experience obtained should then be applied vigorously to the search for additional reserves in similar environments and new districts in new environments. The mineral exploration geologist's most important tools are his ability to analyze the geologic framework of known deposits and the imagination and energy that he devotes to applying knowledge acquired to the search for additonal reserves. Pasteur could well have been talking about mineral exploration when he said "Chance favors the prepared mind." So does discovery.

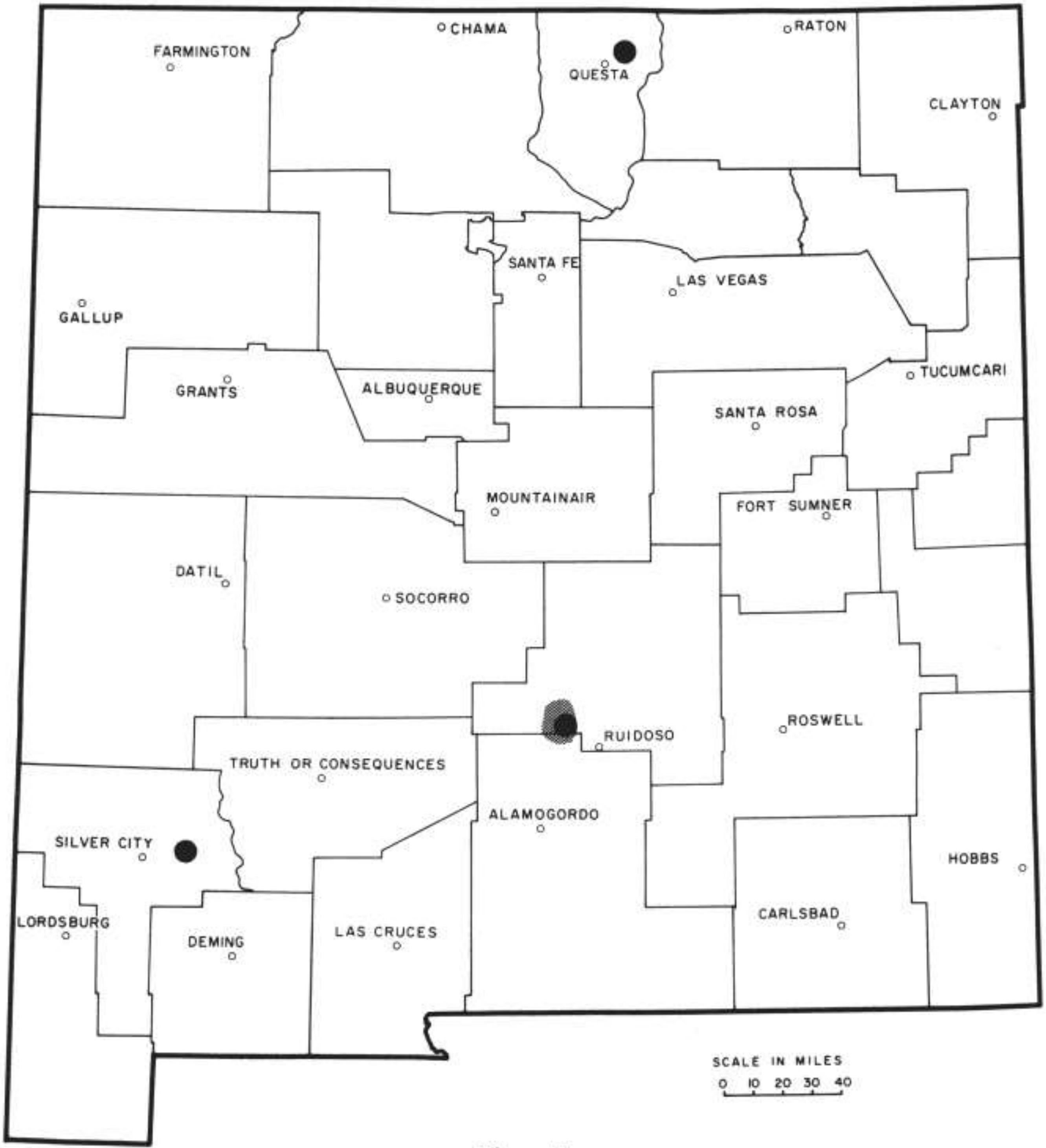


Figure 11
Molybdenum exploration in New Mexico

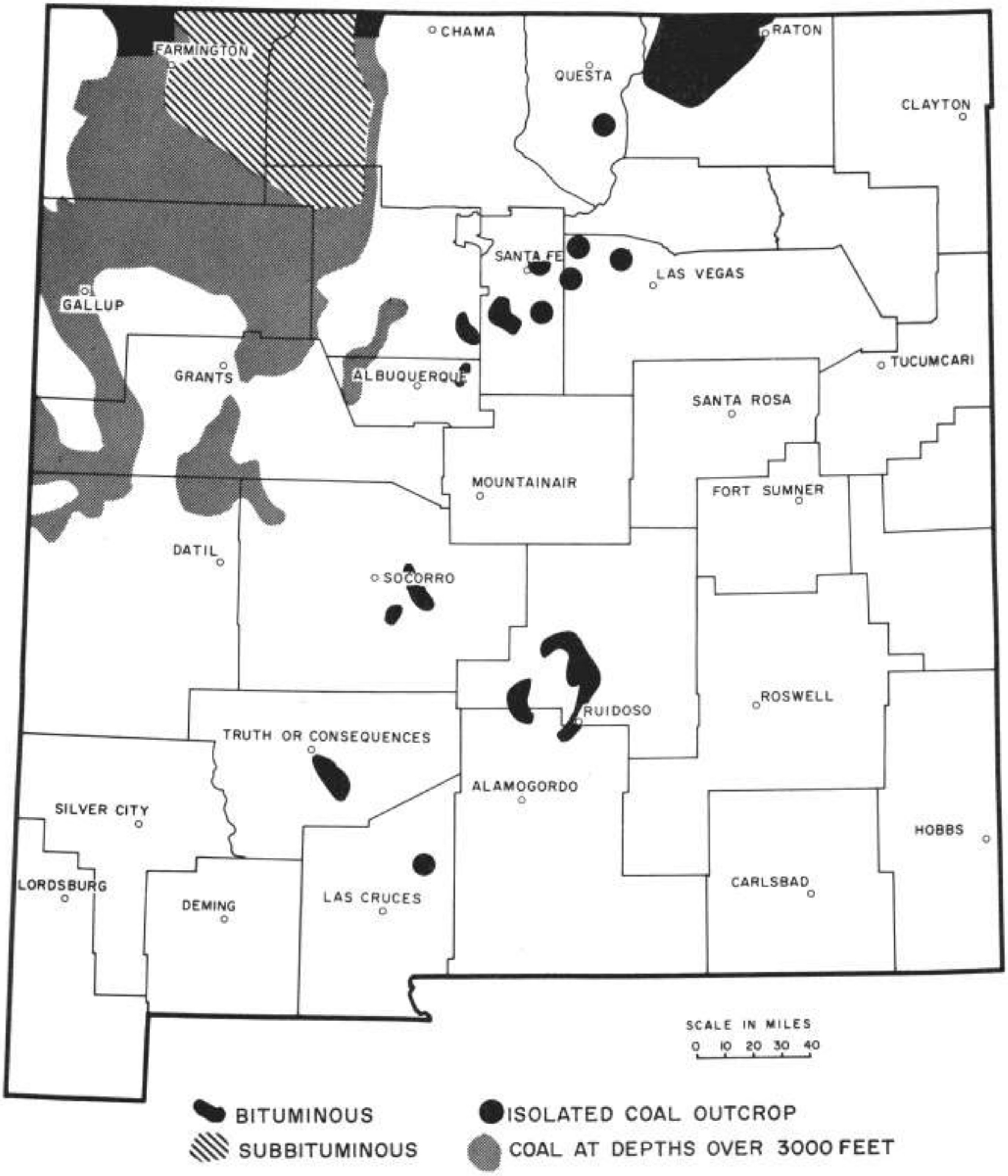


Figure 12
Coal fields of New Mexico

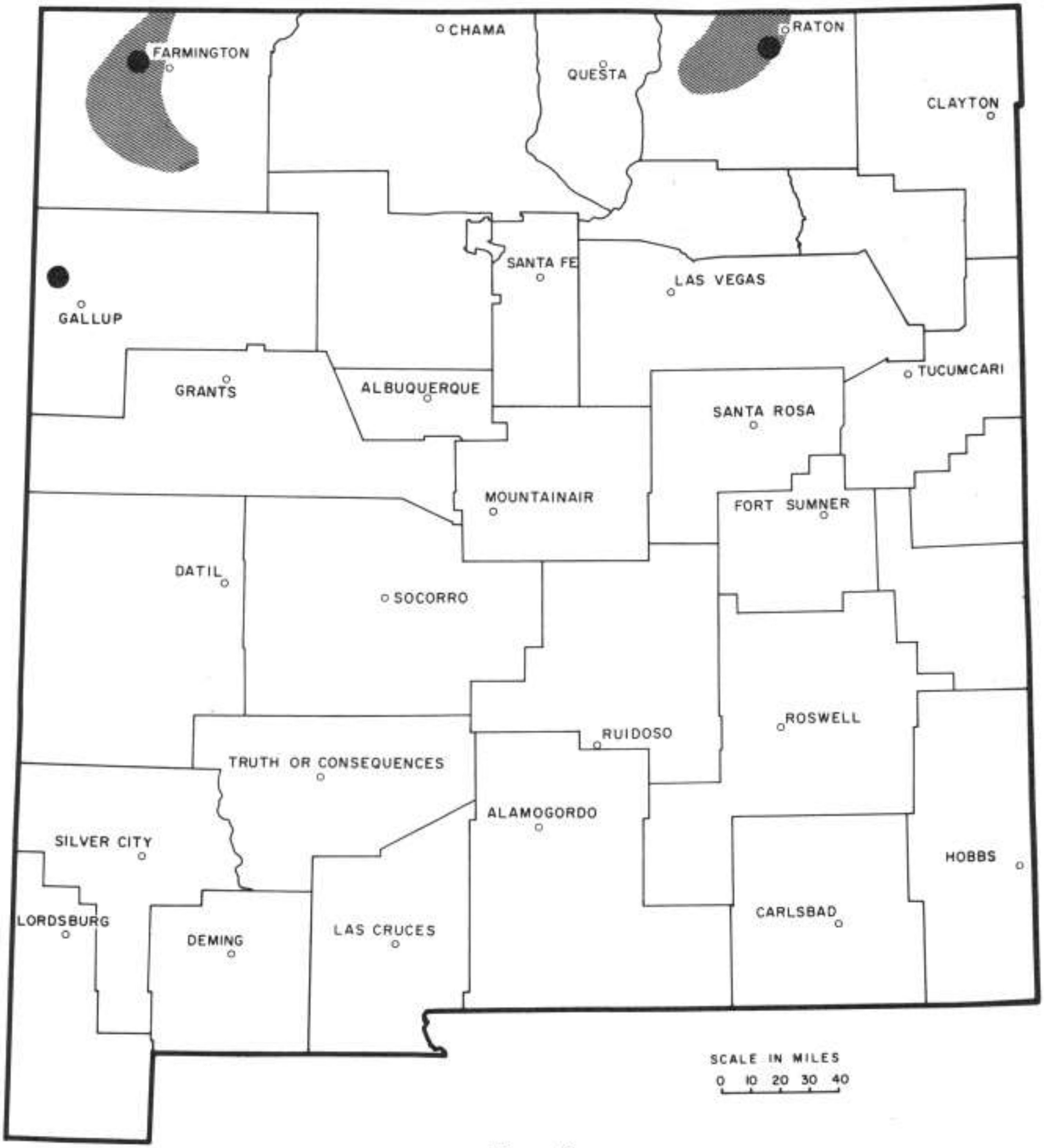


Figure 13
COAL EXPLORATION IN NEW MEXICO

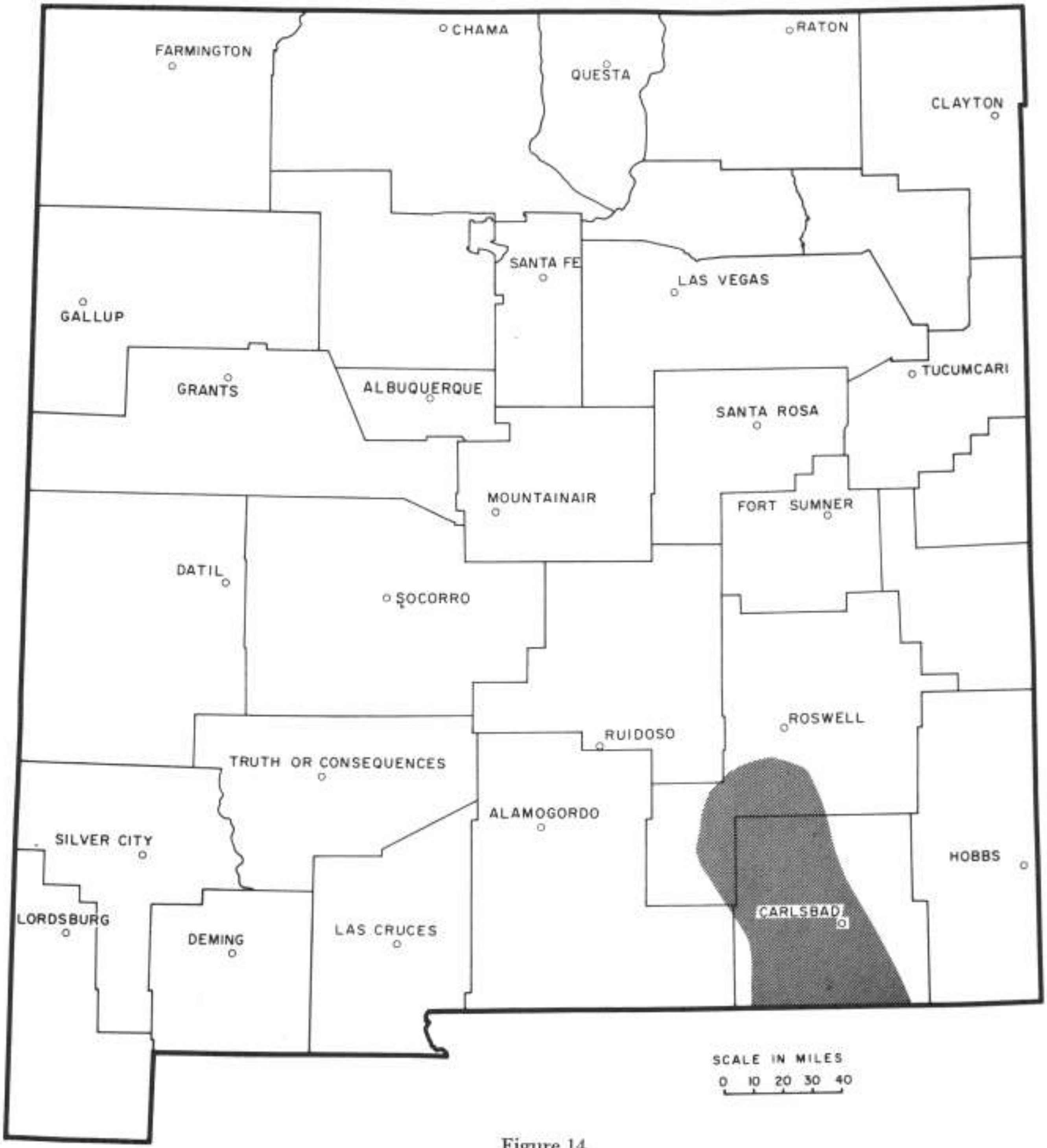


Figure 14
SULFUR EXPLORATION IN NEW MEXICO

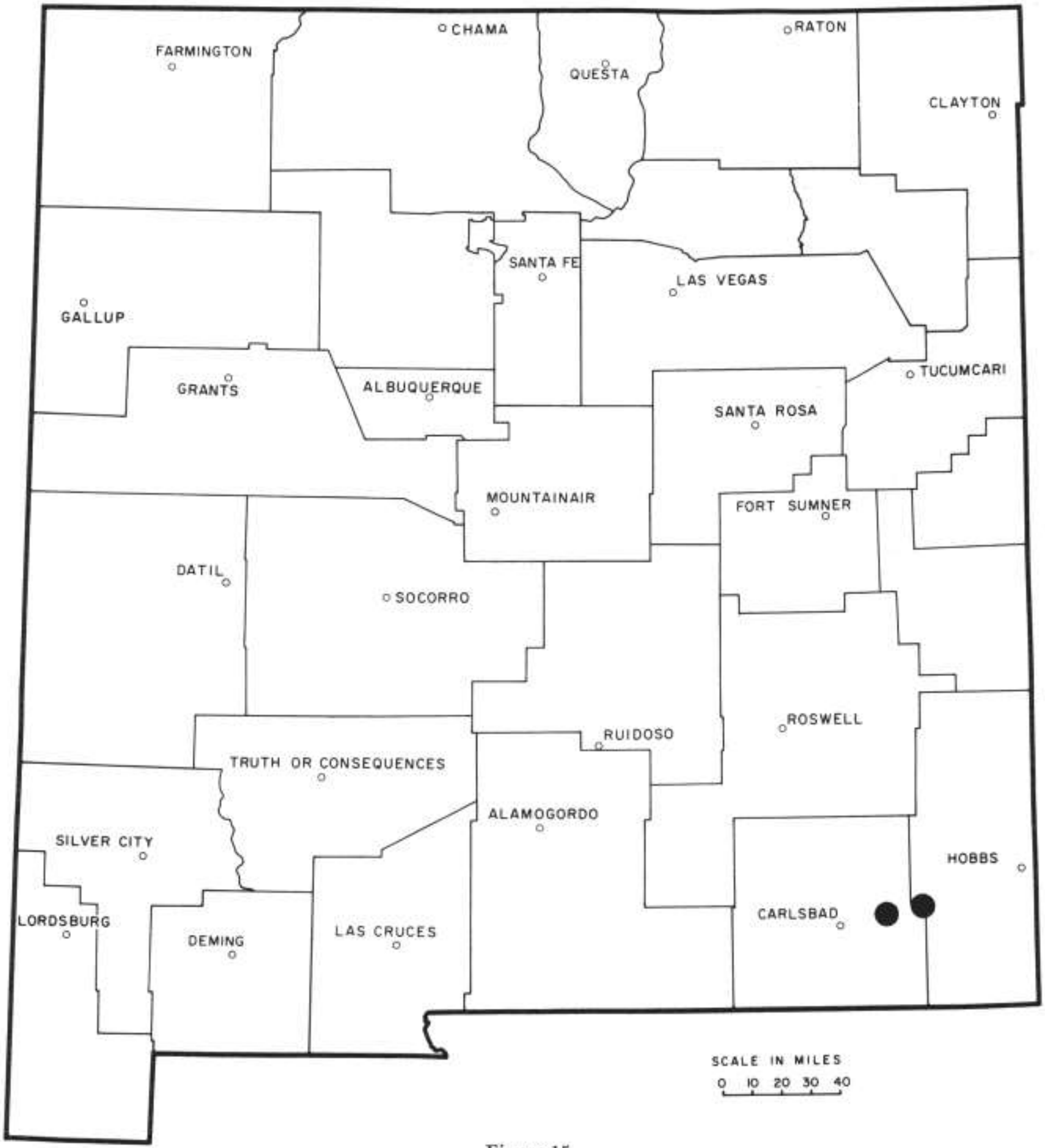


Figure 15
POTASH DEPOSITS IN NEW MEXICO

The Effective Use of Exploration Technique

by Douglas R. Cook
Humble Oil & Refining Company

This paper is adapted from a presentation given at the annual A.I.M.E. meeting held in New York. I hope it will prove both informative and provocative. I have incorporated the topics of our conference theme, with special reference to recent mineral discoveries, successes and failures in exploration, cost of discovery, new ideas in exploration, and the effective use of exploration techniques. Improvements in these areas will result in more efficient exploration; that is, we will obtain more relevant data per exploration dollar and will thereby reduce the cost of discovery. I acknowledge the assistance of my colleagues for their help and also Humble Oil & Refining Company for permission to present this paper.

Specific data for Canadian discoveries have been compiled by Derry for the period from 1951 through 1966 (fig. 1). The implications of these data are quite alarming. Examining the relations of Canadian ore discoveries to exploration expenditures, one marks the decrease in the number of discoveries in spite of increasing expenditures. The data suggest that an increase in sophistication of techniques failed to increase the discovery rate in Canada. In fact, the opposite is indicated.

The data presented at the C.I.M.M. symposium on the future of the Canadian mineral industry, held at Ottawa in 1967, indicated that about 150 mines have started or restarted in Canada since 1955, but more than half of these were discovered prior to 1950. It is evident that the Canadian mining industry is expanding as a result of past discoveries. The data show that it cost 3.5 million dollars to find a deposit in- the period 1951 to 1957. This is in sharp contrast to exploration costs of twenty-two million dollars per deposit since 1958. Evidently this cost is still increasing. In spite of these discouraging statistics, some very profitable deposits have been found in Canada since 1955, such as the Thompson, Boss Mountain, Mattagami, New Hosco, Orchan, Brunswick, Anacon, Heath Steele, Texas Gulf, Chibougamau, Pine Point, Pyramid, Vangorda, B. C. Molybdenum, and Cominco's. Highland Valley deposits. Just a few of these great deposits will, pay the 650 million dollars in cumulative exploration expenditures and interest in Canada from 1951 through 1966.

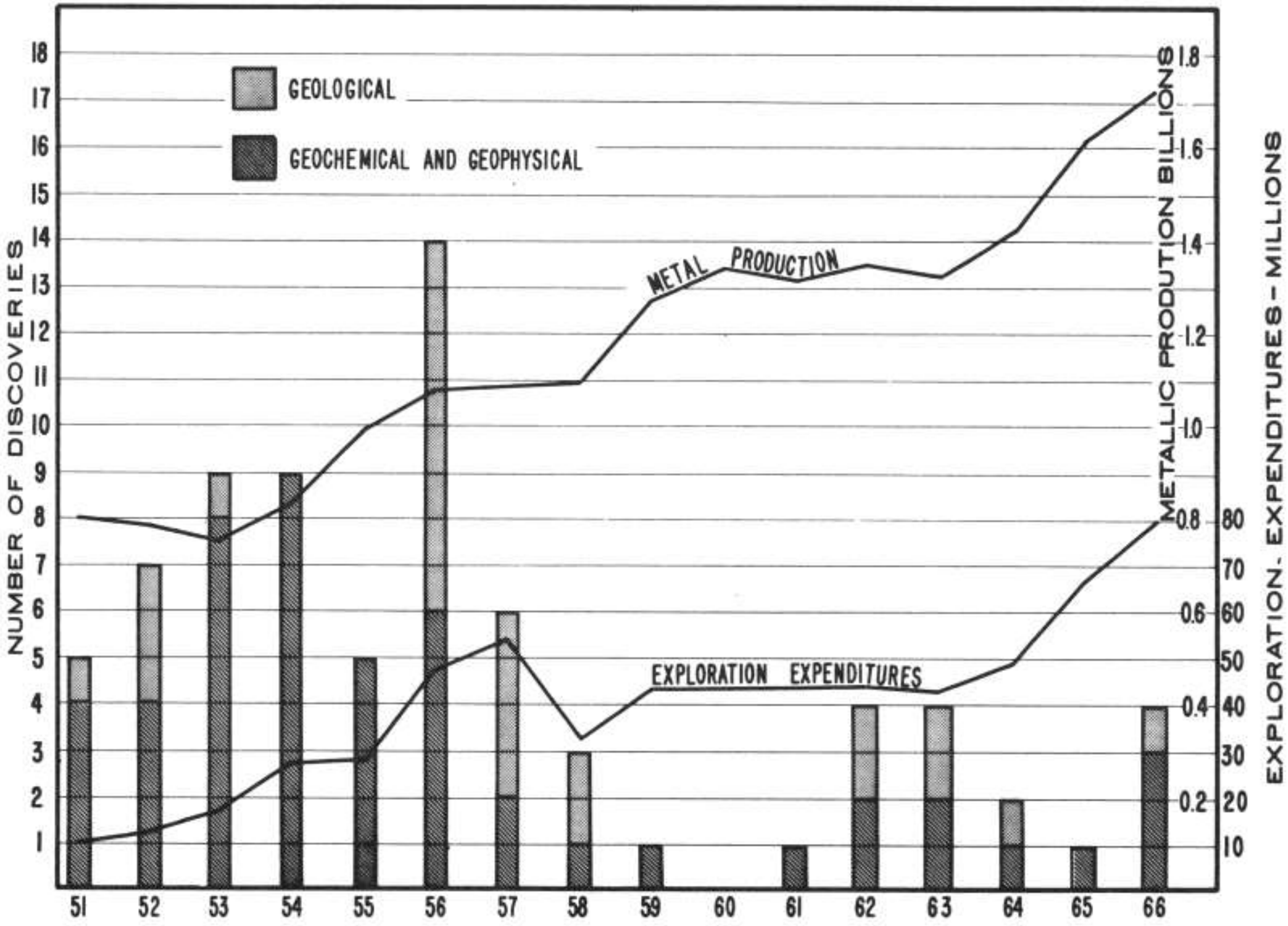
Even fewer discoveries are being made in other countries, such as Africa, Australia, and South America. The discovery record in the United States is thought to be more rewarding than in Canada because the average size of the new deposits appears to be significantly larger. In fact, the number of recent discoveries suggests a reversal to the trends described above, such as Lakeshore, Pima, Mission, Safford, Yerington, Kalamazoo, Burgin, Carlin, Henderson, Twin Buttes, Ithaca Peak, and the New Missouri lead belt. Data concerning exploration expenditures per discovery for the United States are very difficult to compute, although they are probably somewhat comparable in magnitude with Canadian expenditures. It is significant that more than half of the new discoveries in the United States are either porphyry copper or stockwork molybdenum.

EXPLORATION FRAMEWORK

The improved use of exploration techniques, as well as other suggestions presented here, is an integral part of the exploration framework. These techniques must be placed in perspective with each other as well as other exploration elements to better appreciate their significance and interaction in the exploration sense. The exploration framework is summarized in Table 1 and described below.

The objectives of an exploration program need clear definition when the program is conceived. They should be established in terms of commodities sought by discovery or acquisition, financial return expected, funds and time available, and capacity to assume the risks involved. Once established, objectives are not static but must be continuously re appraised because of changing economic and political factors. The exploration objectives are clearly one of top management's functions and should be integrated with over-all corporate policy. The failure to establish clear objectives or to modify them according to changing corporate goals has produced fatal results for a number of exploration programs. Nothing is quite so frustrating to the explorationist as to find, after expending considerable effort, that his discoveries no longer fulfill corporate objectives. On the other hand, a continual drain of funds without any visible sign of satisfying the objectives is likely to test severly management's perseverance and confidence.

The group accountable for exploration results must plan the exploration strategy in terms of the objectives set forth by its management. Planning at this level is concerned with critical questions; such as, What do we look for? Where will we find it? How is it to be found? The answers to these questions depend on the characteristics of ore bodies sought, techniques available for detecting the ore bodies, availability of well-qualified personnel, and competition for land. The selection of continental or regional-sized areas for the exploration program is one of the most critical decisions, since it will influence all future results. Some of the factors involved in this decision are nongeological because they concern politics and economics. All available data must be carefully scrutinized, assimilated, and synthesized



ADAPTED FROM D. DERRY

FIG. I

Figure 1
CANADIAN ORE DISCOVERIES

TABLE 1. THE EXPLORATION FRAMEWORK

OBJECTIVES

Establish an exploration philosophy acceptable to top management. Decisions on the following items are of critical importance to the development of a policy:

1. Select commodities for discovery or acquisition to satisfy corporate goals. Decisions will relate to corporate growth, needs for diversification, market penetration, and new uses of materials.
2. Identify acceptable return on investment and payout time in relation to equity or debt financing.
3. Establish the capacity to assume risks in terms of price projections for commodities, cost projections for construction and operations, financing and political uncertainties.
4. Provide for adequate time to implement an exploration program and sufficient funds to provide a reasonable chance of success to overcome unexpected runs of bad luck.

PLANNING

What mineral deposits do we seek:
  Determined by commodities needed
Where will we find them:
  Related to favorability of geology, economics, politics
How are they to be found:
  Procedures include prospect examination, elephant country approach, saturation approach, and concept-oriented approach.

EXPENDITURE CONTROL

Get maximum use of exploration resources through effective budget control.

Exploration expenditures for individual undertakings should normally be limited by the potential profitability of deposit sought X probability of discovery.

USE OF TECHNIQUES

Selection of techniques based on their discrimination capability.
Sequential use of techniques to reduce the area of interest.
Recognition of new exploration opportunities.

TESTING FOR A DISCOVERY

Surface sampling
Trenching
Discovery drilling
Preliminary evaluations

SAMPLING THE DEPOSIT

Development drilling
Bulk sampling
Pilot plant

ECONOMIC EVALUATION (Return on Investment)

Mineral inventory
Metallurgical tests and metal recoveries
Mine simulation
Demand for commodities and projected prices
Capital requirements for land, plant, and equipment
Cost of operations, sales, and overhead
Financing costs
Taxes
Profit margin

to develop a meaningful plan and the creation of useful concepts. Several different exploration approaches are currently used, depending on the nature of the terrain, presence of postore cover, and degree of surface oxidation and leaching.

Probably the most well-established exploration approach is the examination of prospects described in the literature and documented in company files. New submittals are also encouraged from prospectors and promoters. Since most prospects have been previously examined by competent exploration geologists, it becomes a question of recognizing new features or developing new ideas of ore localization to establish unrecognized exploration opportunities. The relative effort devoted to this type of work is a continuing problem of those responsible for planning an exploration program. Failure to make any prospect examinations will identify the group as being nonreceptive to submittals from the public, and it is thus unlikely to take advantage of new opportunities generated outside its organization.

A successful variation of the prospect examination is the "elephant country" approach, whereby mining districts and ore-body clusters are re-evaluated for exploration opportunities.

A saturation type of exploration approach is frequently used in areas of thin postore cover, where all relevant techniques are applied in a systematic manner over wide areas. This approach is used, for example, in the Canadian Shield in the search for massive sulfide bodies under a thin postore cover.

The concept-oriented approach is a variation of the saturation approach, whereby specific geologic and mineralogic associations are used as a guide to a systematic exploration program. This approach has gained growing acceptance during the last decade, especially by the integrated exploration groups, with research staffs and specialists in the use of geophysics and geochemistry. The essence of this approach is the guidance of a systematic exploration program by the use of specific geological and mineralogical associations. In some instances, the approach can extend to systematic use of certain exploration techniques where geologic guidance is the focus of the program. The successful application of the concept-oriented approach requires the careful study of mineral associations with specific geologic environments. These studies will, in some instances, also lead to the definition of metallogenetic provinces. Examples of deposits discovered as the result of applying a geological concept are Mission (use of halo mineralogical characteristics in defining a target under gravel cover), Kalamazoo (blind ore-body discovery based on application of a fault concept), Kennecott's Safford deposit (use of halo mineralization in projecting an ore body under volcanic cover), INCO's Ely deposit (recognition of sulfides at the base of a layered gabbro), Carlin—Cortez discoveries (fine disseminations and colloidal gold in previously unrecognized geological environments), New Missouri lead belt deposits (blind ore bodies found by testing favorable stratigraphic facies adjacent to Precambrian domes), and Henderson (a blind molybdenum ore body found through structural projections in a favorable geologic environment).

One of the better methods of making maximum use of available exploration resources is effective expenditure control. There is generally no lack of available exploration opportunities; the problem involves setting priorities between the undertakings so as to allow the best chance for achieving the ojectives of the program. Estimates of discovery probability for individual undertakings are particularly useful in establishing priorities as well as for obtaining a guideline for exploration expenditures. The maximum expenditure that logically can be made on an individual undertaking is approximated as a product of the potential profitability of the deposit sought and a factor reflecting the probability of discovery. For instance, if an exploration group thought it had a possibility of finding a hundred-million-dollar ore body in a particular area with a chance of discovery of one in fifty, the group would be justified in spending a maximum of two hundred thousand dollars in the search. Obviously, this is just a rough guide, but is quite useful in setting priorities between projects. This exercise helps an explorationist by preventing him from "falling in love with a prospect" and conducting an exhaustive search, only to find the potential rewards are out of proportion to the exploration funds expended.

CLASSIFICATION AND USE OF TECHNIQUES

To discuss some of the more specific uses of exploration techniques, it is useful to start with a definition and classification. *Exploration techniques* is defined here as the set of procedures of observation, measurement, and interpretation of the characteristics (geological, physical, and chemical) of mineralized areas and their associated effects. *Techniques* comprise the data-gathering methods the explorationist uses to test concepts of ore localization. The location, size, shape, and composition of unusually high concentrations of potentially valuable elements associated with crustal rocks are tested by physical work such as drilling, trenching, or underground excavations. Exploration techniques generally involve various combinations of geological, physical, or chemical measurements, which are graded by the writer into three broad categories on the basis of their discriminating capabilities. The following description, although not necessarily comprehensive, is intended to provide numerous examples in each category.

Techniques placed in the first category possess high discrimination capabilities for the detection of ore-grade material, such as visual observation or ore exposed at surface; gossan and leached capping appraisal where a high degree of confidence can be placed on the interpretation; ore-boulder tracing to locate source of ore; and scintillometer and berylometer measurements for the detection of radioactive minerals and beryllium. Since a minimum of geological knowledge is needed for the successful application of these techniques, they are attractive to the untrained prospector. This does not imply lack of value to the professional explorationist; on the contrary, some of the techniques listed are commonly ignored in favor of the more "sophisticated" scientific methods.

Techniques in the second category are highly capable of discriminating mineralization from other earth materials but, as presently developed, are less successful than those in the first category in distinguishing between barren and valuable minerals; therefore, less confidence can be placed in their reliability for ore detection. Such techniques include electromagnetic surveys, induced polarization surveys, self-potential surveys, resistivity surveys, rock geochemistry, and soil geochemistry. These are used primarily in areas with postore cover, such as the Canadian Shield, and in terrain with extensive leaching and/or postore pediment cover, such as the arid southwestern United States. Unfortunately, undue confidence is often placed in these techniques as presently used.

Techniques with a low discriminating capability for the direct detecting of both ore-grade material and sulfides are in the third category and include color anomaly studies, aerial photography, seismic surveys, gravity surveys, biochemical geochemistry, water geochemistry, stream sediment geochemistry, geothermal studies, and airborne remote sensing. Although these techniques have a low discriminating capability for the direct detection of ore bodies, they can be of value in creative geologic studies and in the regional reconnaissance phase of exploration. They are frequently used to define general areas of favorability, but more definitive exploration techniques are subsequently initiated to identify ore targets.

It is essential that sound geologic guidance be used to interpret the data derived from the techniques listed in this section. A successful program involves the integration of all the relevant exploration data, particularly the integration of geochemical and geophysical measurements, with the geological information.

SOME PITFALLS IN THE USE OF EXPLORATION DATA

Many weaknesses are evident in the use of exploration data, including the unreliability of measurements, poor interpretation of results, negative use of certain data, improper selection of techniques, acquisition of irrelevant or useless information, and sometimes the unrealistic desire for technological breakthroughs. An attempt is made here to identify these pitfalls.

One of the most aggravating problems in mineral exploration is the difficulty of obtaining consistently accurate geologic measurements. Geologic maps too often combine fact and interpretation without giving a clue to where one begins and the other ends. As a consequence, maps of the same area by two competent geologists commonly show remarkable differences. Part of the difficulty lies in the failure to standardize mapping techniques and in the lack of general acceptance of standards—if set. The distinction between a factual outcrop map with descriptive lithologies and interpretational maps showing formational boundaries is a case in point. Inconsistencies involve such critical items as nomenclautre and identification of igneous rock types, distinction of data obtained from outcrop or rock float, recording of linear and planar features, and identification of alteration features based on reliable field criteria and laboratory identification. Since geologic maps are records of geological facts in their correct spatial relationship, they represent the basis for interpretation of geochemical and geophysical measurements. They should convey a historical, physical, and chemical understanding of the terrain. Inadequate and erroneous geologic data multiply the problems of interpretation. For example, detailed outcrop maps of mining districts prepared by the Geological Survey of Canada are, in my experience, most useful in exploration.

A common failing in mineral exploration is the collection of geochemical data without appreciation of the multitude of variables influencing each sample point. For example, the influence of climate, topography, rock reactivity, and soil types on the metal values of stream silts is known only in a vague qualitative sense. Sample results may be used without knowing the limits of accuracy and precision of the analytical techniques employed. Only infrequently are duplicate samples collected at any locality to determine the variance of the values.

Little geologic guidance is given to the choice of physical characteristics to be measured by geophysical techniques and little use of geology is made in the final geophysical interpretation. Geophysicists tend to distrust the work of geologists for reasons cited above, and most geologists fail to make the necessary effort to understand the use and limitations of the geophysical techniques. Frequently, geophysical measurements are made without an appreciation of the mineralogical components in the material being measured and how variations in these components will affect the results. This illustrates the necessity for effective communication between geologists and geophysicists and and the necessity for integrating the various types of data.

Interpretation of exploration data should be based on a good understanding of the characteristics of the ore bodies being sought and the variables of their environments. We frequently use empirical or analogous reasoning but fail to obtain -the necessary criteria that establish similarities of a particular prospect to the type of deposit sought or variations from it. Unfortunately, model studies with reliable quantitative data are rare in the literature. Universities can provide a major contribution to the development of our country's resources by an emphasis on this type of investigation. Very little is known about the transport of metallic ions in natural fluids, how metals are captured by stream sediments, the influence of seasonal changes on geochemical results, and the influence of reactive materials. The recent article by Hansuld, entitled *Eh and pH in Geochemical Exploration*, emphasizes the variables likely to be encountered in analysis of geochemical results and our lack of understanding of the basic chemical processes involved. It is therefore not surprising that for lack of better information, some geochemical anomalies are rated only according to their size and intensity. More important, the over-rating of large anomalies might result in ignoring the subtle but more significant ones. For example, a large geochemical anomaly might reveal an area of high sulfide content with little associated ore, whereas the ores might characteristically occur peripheral to a barren sulfide body. Furthermore, geochemical and geophysical anomalies need to be related with the particular geologic environment.

Although indirect guides to ores are poorly understood, they frequently are used in a negative sense to eliminate ground from exploration. More importantly, promising areas defined with valid geological criteria may be abandoned because of negative geochemical or geophysical results. Geochemical prospecting has been used in appraisals of primitive areas to supplement regional mapping and prospect examinations. The limitations of these geochemical techniques are not adequately defined. It is important that everyone recognize that most exploration techniques are search-oriented and cannot be used to appraise ground systematicallyfor all types of ore bodies or to provide mineral inventories. If large geochemical anomalies are absent, the impression is held that the terrain is unmineralized and can be withdrawn from exploration. Geochemical reconnaissance should be used only as a coarse filter; the lack of outstanding results does not negate the possibility of mineral deposits in the area. This is of particular concern when ore bodies can be hidden, by either preore or postore cover.

The selection of the appropriate techniques in exploration work is one of the most critical problems faced by the explorationist. An important distinction exists between an effective exploration technique—the best technique to solve the ore-finding problem—and efficiency in exploration methods—making good observations and measurements at a minimum cost. First, what is the objective of the ore search in terms of ore-body characteristics? Second, how relevant will results from the technique be in terms of the information needed? In fact, some of the best ore-body concepts are achieved by working with existing data, not new information. The indiscriminate use of geosurveys compounds the problem of interpreting the data. There is no lack of anomalies in most types of geophysical or geochemical surveys; the problem is to determine their significance for the detection of the ore body. Geological "noise" may very well mask the features sought. The danger of backward exploration is ever present; that is, run a geosurvey to find an anomaly and then try to explain the anomaly by looking at the geology. The improper use of techniques also applies to geology through useless mapping or bad choice of features for mapping. A geologist may feel an obligation to make a geologic map in deference to his training without a proper appreciation of the needs to be served by the map.

It is a natural tendency for an explorationist to collect as much information as rapidly as possible in the hope that some of it will be useful. This is a fallacy because the mass of data invariably produces mental indigestion. It is unreasonable to expect that data will find an ore body. A proliferation of data, some of which is relevant and some of which is not, compounds the problem of interpretation and analysis. Statistical methods such as multiple regression and factor analysis have not yet become sufficiently sophisticated to identify important ore-finding criteria; however, research in this area is very well justified for future use.

It is the hope of all those responsible for the management of exploration funds that a new technical breakthrough will provide a rapid and inexpensive method for the discovery of ore. This desire has resulted in overreaction and overuse of certain new developments, such as airborne magnetics, electromagnetics, water geochemistry, and induced polarization. This does not imply that these techniques are useless; rather, that they did not live up to overoptimistic or unfounded expectations because their limitations had not been sufficiently appraised.

SUGGESTIONS FOR IMPROVING THE PRESENT USE OF EXPLORATION TECHNIQUES

There is an urgent need in exploration for multiple working hypotheses and unbiased viewpoints on genetic theories and their application. It is easy to polarize our thinking by a particular genetic hypothesis in vogue or by the need to defend a favorite theory. Some may consider us unprofessional if we do not have a bias for a particular school of thought on mineral genesis. This reaches a ridiculous extreme when one is asked if he is a hydrothermalist or syngeneticist as if this were a prerequisite for entry into a selected club. It can be professionally fatal to join such a club, for genetic theory must be adjusted to field facts. A real danger of theory influencing selection of field data is ever present.

Geological maps on both regional and local scales are the basis for the selection of areas and the interpretation of exploration data. There is a continuing demand for better maps. Federal and state geological agencies can assist on the regional scale by updating existing maps and by filling in many gaps that currently exist.

We need to quantify our geologic observations against reliable measurement standards. How often are alteration or mineralization features recorded on maps without a statement of criteria used to distinguish the map units? Fact and interpretation in our data should be clearly distinguished. This applies particularly to the preparation of various types of map data.

A major problem confronted by the explorationist is the integration of various types of geological, geochemical, and geophysical data. A clear synthesis of all the available facts pertinent to the exploration problem provides a basis for the development of new ideas and a better appreciation of the gaps in our knowledge. One of the basic requirements is to present the data in such a form thay they can be integrated as to quality of measurements, distribution of information, and representation at a common scale.

Exploration problems require good definition before a technique is selected. Techniques are sometimes indiscriminately used because of their availability rather than their suitability for a particular purpose. Once a technique is chosen, the limitations of the method should be carefully ascertained. Of importance is the need to appraise the effect of the geologic environment on the particular technique to be used. The acquisition of more data than required, or the collection and use of irrelevant data, tends to confuse the interpretation and reduces the exploration efficiency. The point to be stressed is not only the importance of sound geologic exploration concepts and the use of reliable geologic data in the selection of areas of interest but also the added importance of geology in the selection, planning, and interpretation of geochemical or geophysical survey results. In fact, virtually all exploration programs are initiated by a geological concept. The use of geology alone will not result in many ore discveries, but it provides an essential link in the use of other exploration techniques. All techniques complement each other.

Exploration techniques must be used in a positive sense to identify ore targets. The variables that affect the results of exploration techniques are poorly understood, yet negative results are frequently used to eliminate ground from further consideration. Coincident positive indications produced by techniques that measure independent physical or chemical properties are most likely to result in success when interpreted against a background of gelogical data.

SUMMARY

In summary, we have the problem of increasing costs of large discoveries, now estimated at about twenty million dollars per deposit. It is suggested that improved results will be obtained by more thorough exploration planning and by adopting a concept-oriented program. Techniques should be selected on the basis of their discriminatory capability to solve the particular problem at hand. Pitfalls in exploration include problems in data collection and their measurement, problems of interpretation, and the use of techniques. To improve the use of exploration techniques, I suggest more rigid selection based on their discriminatory capabilities. For effective exploration, I must also stress the need to use multiple working hypotheses, to improve the quality of our exploration data, and to give more recognition to the variables affecting the interpretation of these data. The increasing complexities of mineral exploration caused by the need to explore in covered areas, the necessity to use new techniques, and the increasing competitive conditions provide a challenging occupation. The professional explorationist must work in a dynamic environment where there is a free interchange of ideas and information. Support is needed for long-range exploration plans and perseverance to carry them through to a logical conclusion.

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The Industrial Minerals Geologist or Who Killed Clem Kadiddlehopper?

by Lawrence F. Rooney
Indiana Geological Survey

It is a great pleasure for me to be here because my true home is in the West and I am a Hoosier only by marriage.

I imagine for many of you it is surprising to have a speaker on minerals from Indiana, a state better known for Crest toothpaste and the Kinsey Report than for its limestone or gypsum. In fact, I. U. is sometimes known as the school with clean teeth and dirty minds. Unfortunately, I came there too late to benefit from the toothpaste.

I'm sure that everyone here is aware that the industrial minerals comprise just about all mineral resources not included with metals, fuels, and water. It would be inappropriate and probably boring to discuss any of these in detail and only boring to run through a list of some 40 or 50 rocks and minerals in an effort to pick out what is new. What I will do, therefore, is make some general remarks on the value, role, and education of the industrial minerals geologist and cite examples from the geology of Indiana that can be considered new developments in exploration, the theme of this meeting.

Our society is filled with paradoxes of many kinds, one of which was made vivid to me on the trip from Indiana. We are all aware that airlines make a great effort to attract customers through sex; that is, they supply attractive stewardesses who wear miniskirts and disport in a manner that would be hazardous on the ground. But what illicit activity is possible in a tiny metal tube at 30,000 feet when you are squeezed in along with some 50 or 100 other passengers? Compare, on the other hand, the railroads. You can travel across the country for three days in a train carrying a bar and 50 bedrooms, and all the railroad supplies is a few middle-aged porters.

It is another paradox of our present civilization that most of the prosaic, abundant, low-valued industrial minerals are mined in areas of maximum urbanization, whereas the elite and civilized minerals, such as gold and oil, are produced in the less-populated areas. (Not that I wish to classify New Mexico as an underdeveloped nation but, like the rest of the mountain states, it does have some affinity with the Congo and Saudi Arabia in the way its mineral resources have been exploited.)

The distinction between the production of industrial minerals in the eastern and the western states is not so clear as published statistics would indicate, mainly because these statistics are presented on a state rather than a city basis. Production of construction materials, such as aggregate, *has* been large near the western urban centers and has resulted in some of the same problems that we have in the Midwest and the East. Denver is a notable example. Even on a state basis, however, the winds of change are felt. The value of all nonmetallic minerals produced in Montana exceeded the value of all metals as long ago as 1958 (Chelini, 1967, p. 2), and the ratio between the value of metals and nonmetals produced in New Mexico was 60/40 in 1940 and 40/60 in 1966. Certainly, if the Southwest can maintain adequate water production, it can expect growth in industrial mineral production and urban problems that accompany increased population.

So let us assume that the Southwest's time will come and that one day New Mexico and other western states will share the eastern man's burden. The need for geologists who specialize in industrial minerals and urban geology will also grow, but I believe the nature of this need and the way it should be satisfied are not generally realized. Many producers of industrial minerals apparently feel that they do not need geologists because they have been able, so far, to survive and make a profit without geological advice. In my own state, at least one producer of dimension stone believes that the limestone he quarries was deposited in lumps along the sides of hills in the not-too-distant past. And virtually all our dimension-stone producers pay little attention to stratigraphy in selecting core sites. Of course, cores that begin and end somewhere in the middle of the building-stone formation cannot be correlated—not that it really matters, for they are abandoned in the field, unrecorded and unmarked. One producer, a real conservationist, slips the cores back into the drill holes from whence they came. The cumulative exploration waste from decades of such practices is enormous.

Although the dimension-stone producers, for a number of reasons, probably cannot afford a geologist, any company that mines large quantities of earth materials should employ a geologist full time or retain a consultant who maintains a continuous file of data accumulated by the comp any during exploration and development. Such companies include those that mine or produce common, easy-to-find commodities such as gypsum, cement, lime, crushed stone, sand and gravel, sulfur, industrial sand, and phosphate rock.

In addition to maintaining continuous files, these geologists need to keep abreast of all events, discoveries, and ideas that affect their raw material and related raw materials. They need to be bright, well-informed, energetic people capable of top-level management in our technical age—not the Clem Kadiddlehoppers of the profession. I do not know what percentage of the industrial mineral producers employ geologists, much less first-rate men, but my impression gained during the past five years is that many have settled for Clem and his friends.

Still, it is a fact of life that most industrial mineral producers can be classified as small business and cannot

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afford to hire geologists unless those geologists assume other duties, such as mine superintendents. Yet geological information is of great value to these producers, and thus a considerable role has been created for industrial mineral geologists in state government.

As I have pointed out in more detail elsewhere (Rooney, 1965), a state geological survey (or bureau of mines) collects much information on the industrial minerals within the state's boundaries, including geologic maps, measured sections, well samples and cores, chemical analyses, and test data. Some state surveys have been continuing organizations for more than 100 years and have employed hundreds of experts maintaining high standards. They have a large capital investment in equipment and storage space. They have published much information and collected more that is in open file. A mineral industry may come or go, but the survey remains to collect, integrate, and interpret the data. No other organization except the federal government can afford to match this effort, and indeed it would be illogical for any other organization, including the federal government, to attempt it.

Survey specialists in a particular mineral probably know more than anyone else concerning the distribution and composition of that industrial mineral in the state and the most likely areas in which new deposits might be found. It is economically reasonable that such a specialist provide this information to all interested parties, without continually looking under his feet to see if he is stepping on a consultant's toes. Much survey work, therefore, is of the service variety, helping industry locate deposits of suitable material. But most surveys also think it important to lead industry into new areas and to conduct some basic research for which there is no immediate application.

I would like to cite some examples from Indiana that illustrate the role of the geologist in industrial minerals and urban geology and, in doing so, I hope to describe some ideas that are relatively new.

The conflict between the growth of urban centers and the needs of industrial mineral producers is so well known that it need only be mentioned here. Efforts made by many cities to solve traffic, pollution, noise, or other problems by zoning have ignored the fact that minerals are found where they are, not where planners would like them to be. Indianapolis, for example, a city built on one of the state's finest gravel deposits, proposed zoning the metropolitan area a few years ago without attention to the fact that some of the areas reserved for mineral production contain no mineral deposits. This oversight has since been corrected.

Elsewhere in the state, our geologists have assisted limestone and sand and gravel producers, hamstrung by zoning, by finding new sites and by pointing out to county and city planning boards the need to reserve mineral deposits for exploitation, even if the deposits lie within or near the cities. We have also attempted to persuade industry to make a genuine appraisal of the industrial mineral deposits that lie underground both near the cities, such as Indianapolis, and in areas of the state where none are found at the surface. For example, the northern, most densely populated part of Indiana, an area of more than 6500 square miles, does not have one quarry or mine (fig. 1) although crushed stone and agricultural limestone must be imported from considerable distances and bring premium prices.

I am convinced that the possibility of producing crushed stone from an underground mine in northern Indiana has not received a thorough economic analysis and that the reason it has not is a sort of technical claustrophobia that afflicts aggregate producers. Most of them have no experience in underground mining and prefer to stick to what they know. The question in my mind is: Are geologists employed by the large aggregate producers underestimating the potential of underground mining?

But the example of geological effort in industrial minerals that I cite in more detail is the survey's exploration for and research on gypsum in northern Indiana, whose success was heralded by spectacular indifference on the part of the gypsum industry.

Gypsum currently is produced near Shoals in southern Indiana and in a ring of plants in Iowa, Michigan, and Ohio. One of the country's largest markets, the Chicago area, lies at the center of that ring and is served by gypsum imported from the surrounding states (fig. 2).

Some evidence of gypsum in the Devonian Detroit River Formation about 40 miles from Chicago was found in deep wells drilled in the last century. In 1942, the Shell Oil Company No. 1 Smith apparently penetrated some 30 feet of gypsum near LaPorte, but either the cuttings were not believed or the implication of this information was not realized. In the early 1960's, the Northern Indiana Public Service Company took more than 20 cores near Fish Lake in LaPorte County while exploring for a gas storage reservoir and found as much as 25 feet of anhydrite and gypsum of 80 percent average purity in one continuous evaporite body. In the light of the NIPSCO information, we evaluated the cuttings from the Shell test optimistically and undertook a small exploration program of some nine cores, most of them near the town of LaPorte. Added to the NIPSCO cores, they provided a fair picture of the distribution and thickness of the deposits (fig. 3).

At first, we believed these evaporites were deposited in lagoons, but now we believe that they are of the sabhka type similar to the evaporites being deposited near the Persian Gulf. The same origin may apply to deposits of many ages, such as the Cretaceous of Louisiana, Jurassic of Manitoba, Mississippian of Indiana and Michigan, Devonian of Indiana and Iowa, and Silurian of Ohio. In fact, the same origin may apply to deposits in the Southwest, such as those in the Yeso Formation of New Mexico.

Briefly, the sabhka theory proposes that calcium sulfate is deposited mainly as anhydrite nodules in the slightly older, unconsolidated sediments that form the sabhka and that lie just above sea level near lagoons or coastal embayments such as the one shown on the Persian Gulf (fig. 4). Because of the high rate of evaporation, brines carrying calcium sulfate are brought by capillary action from the lagoon or sea into these sediments and precipitated. The nodules grow, excluding the unconsolidated carbonate or clay sediment, and produce a mosaic texture, as seen in Figure 5 *(see also* p1.3 in Weber and Kottlowski, 1959).

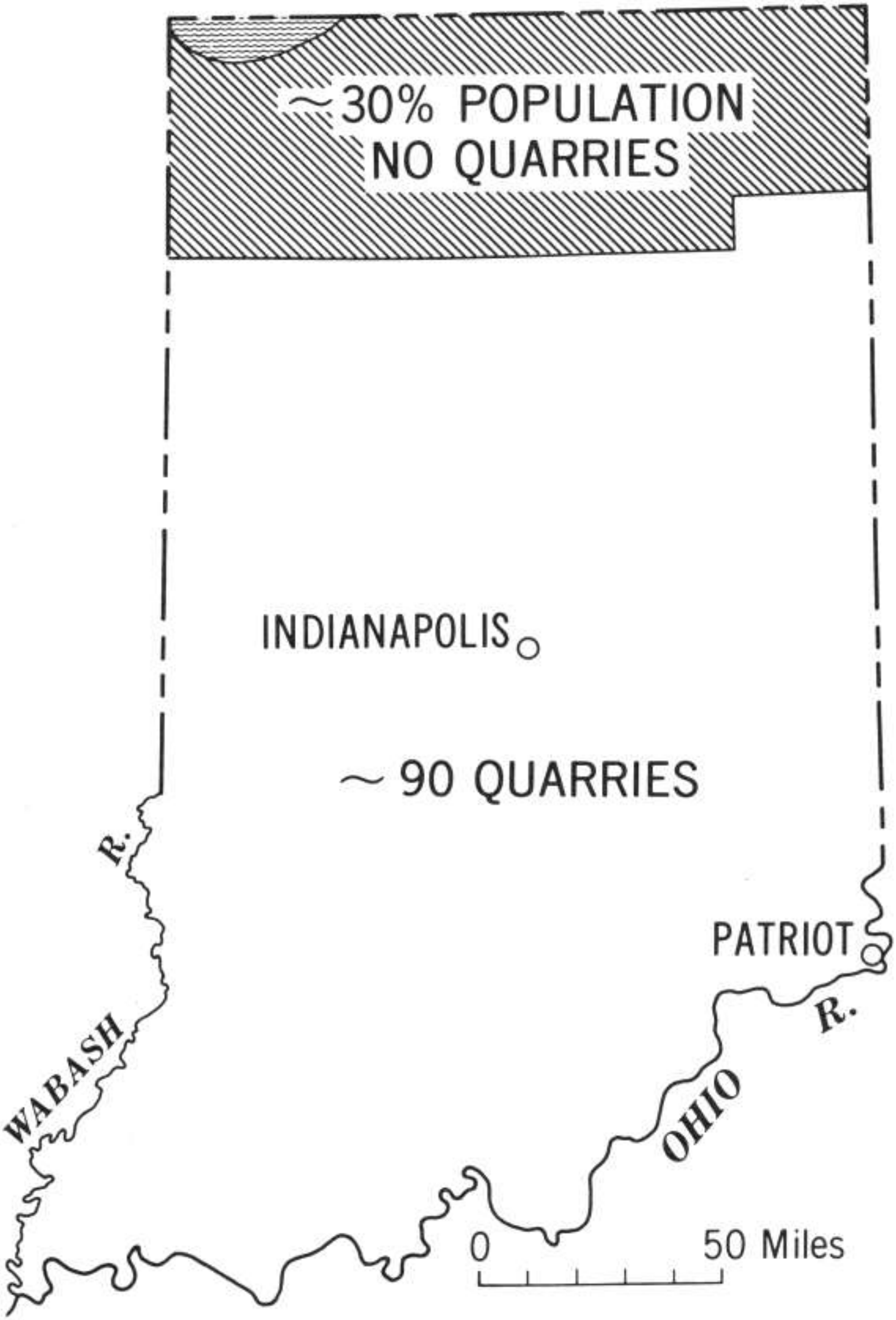

Figure 1
MAP SHOWING PROJECTED DISTRIBUTION OF QUARRIES AND POPULATION IN NORTHERN AND SOUTHERN INDIANA IN 1970

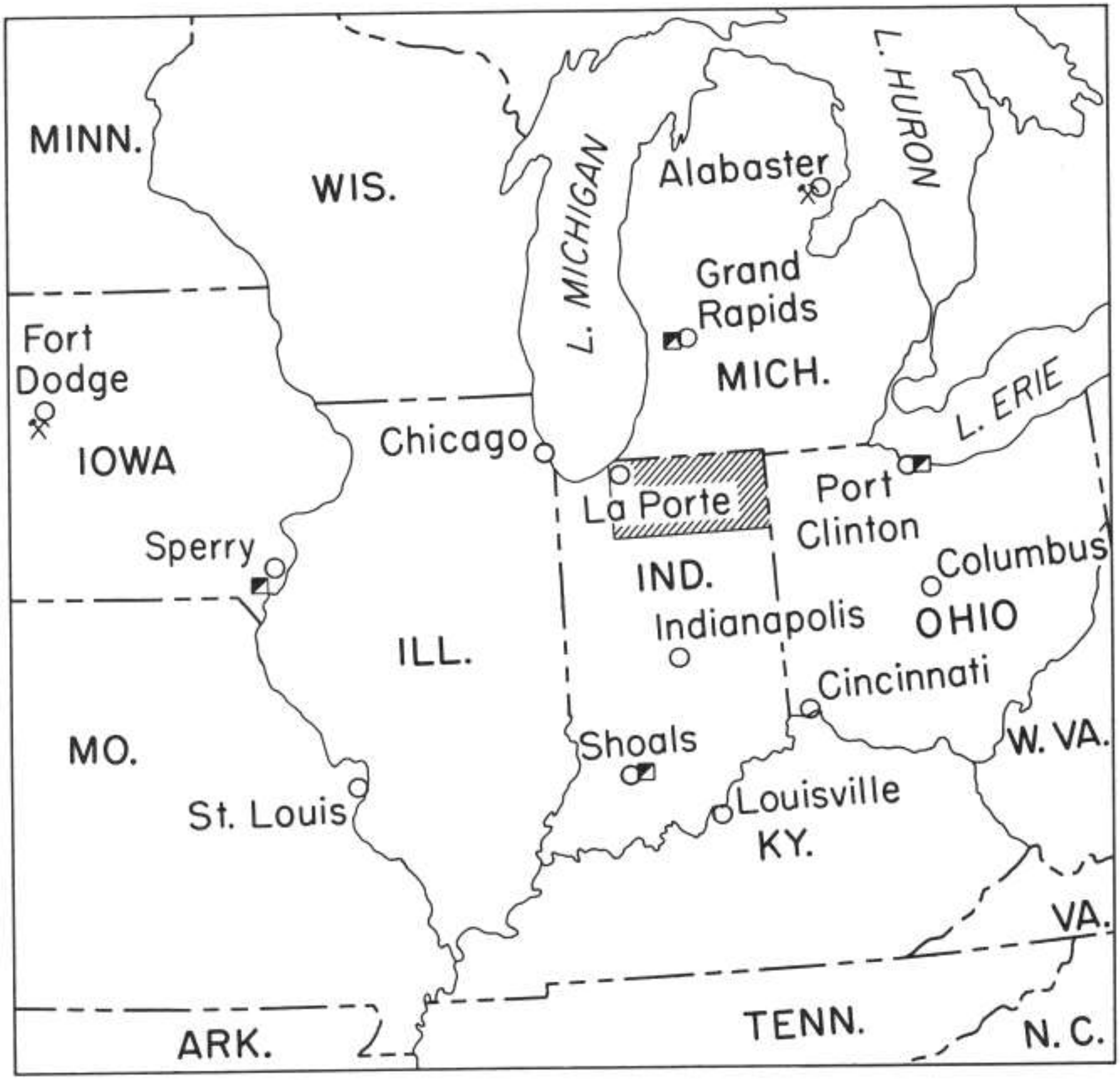

Figure 2

Map of midwestern United States showing location of Gypsum mines and Quarries and general area of Detroit River evaporites in Northern Indiana

(From Rooney, 1965, fig. 1)

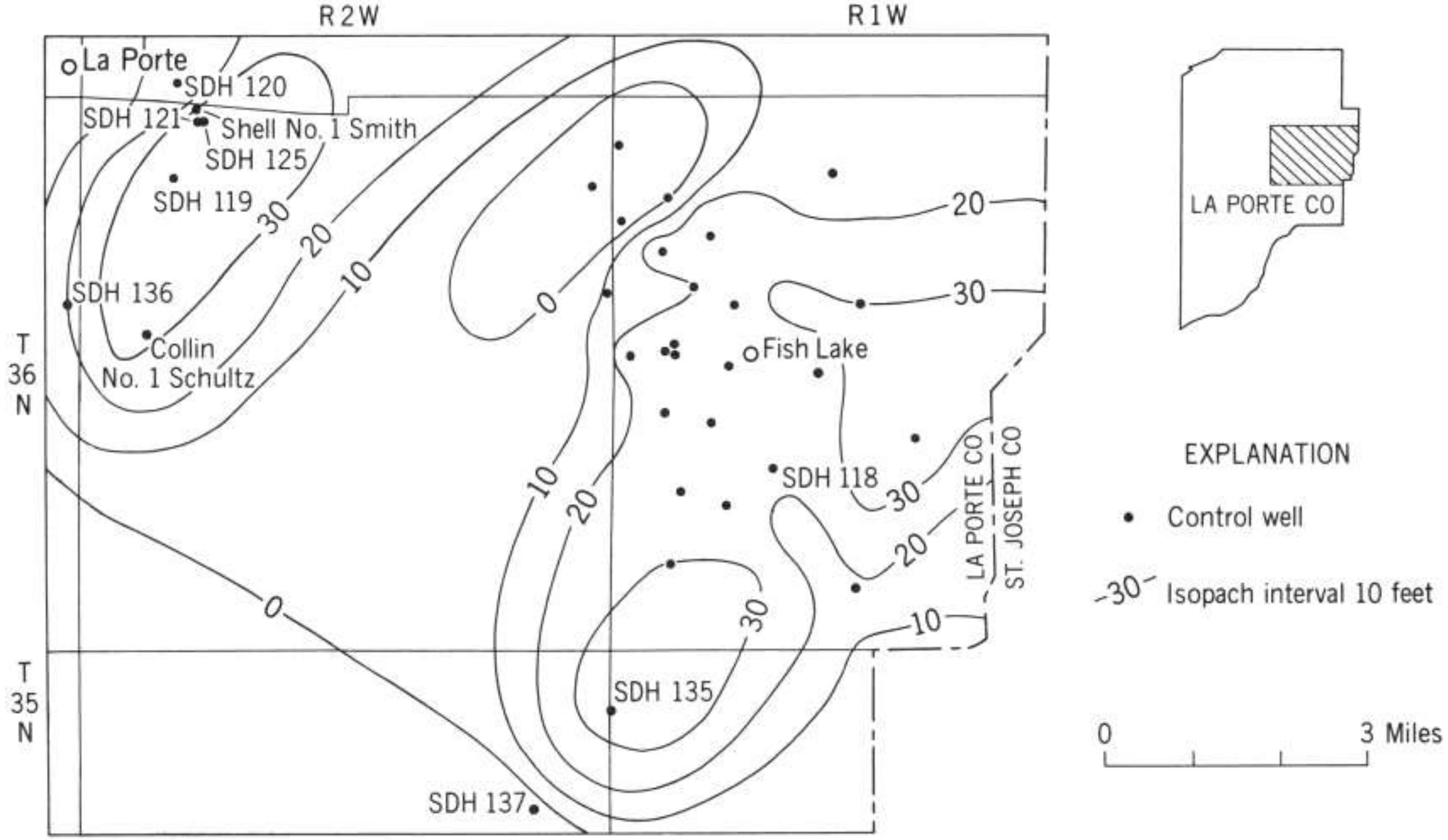

Figure 3

ISOPACH MAP OF PART OF LAPORTE COUNTY, INDIANA, SHOWING THICKNESS IN FEET OF DETROIT RIVER EVAPORITES

"Fractions" denote thickness in feet of gypsum layers at top and base of evaporite unit. (Adapted from Rooney, 1965, fig. 3)

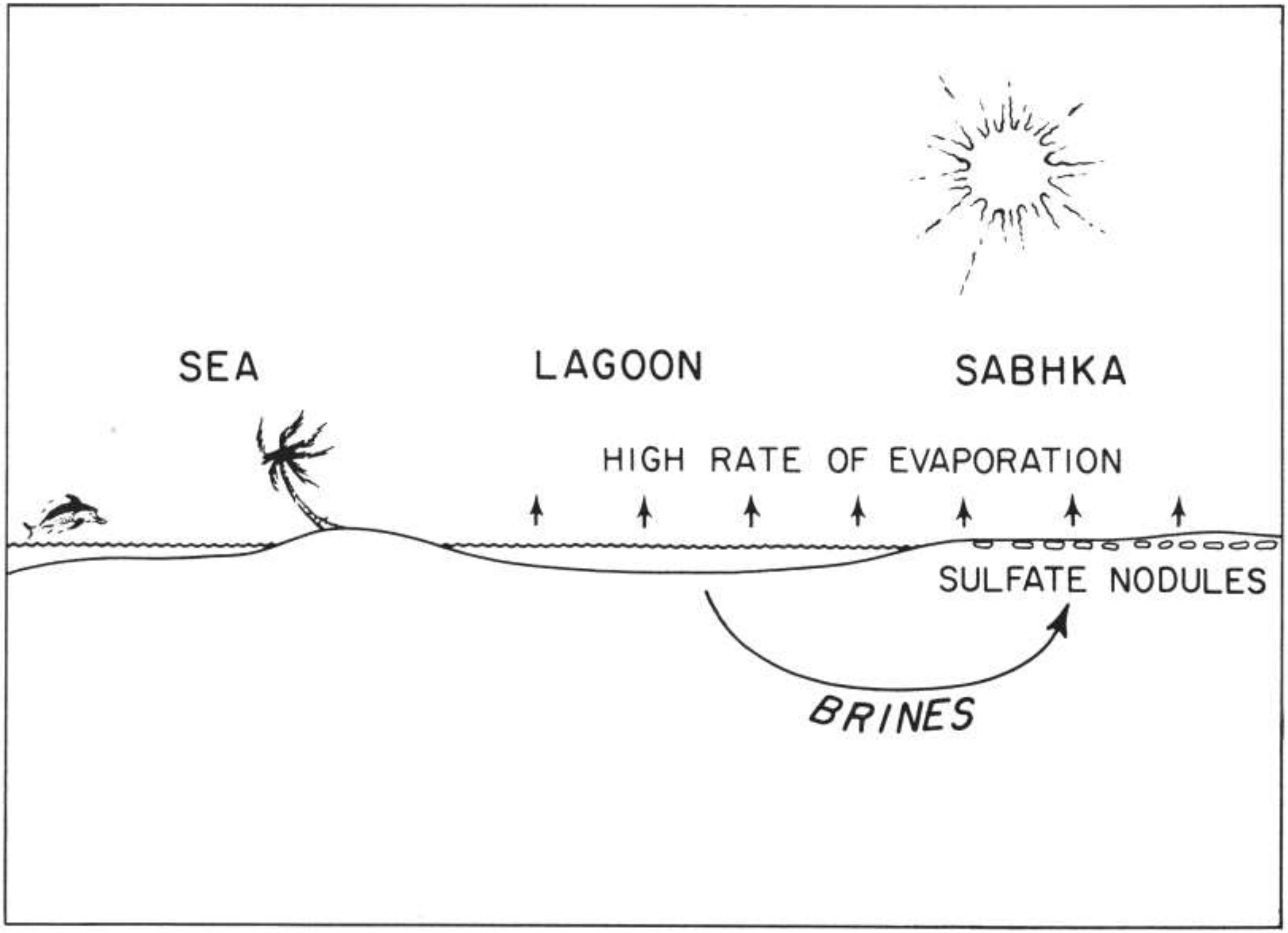

Figure 4
Diagrammatic cross section showing movement of brines and deposition of Nodular Anhydrite in a Sabhka
(Adapted from Kinsman, 1964, fig. 2)

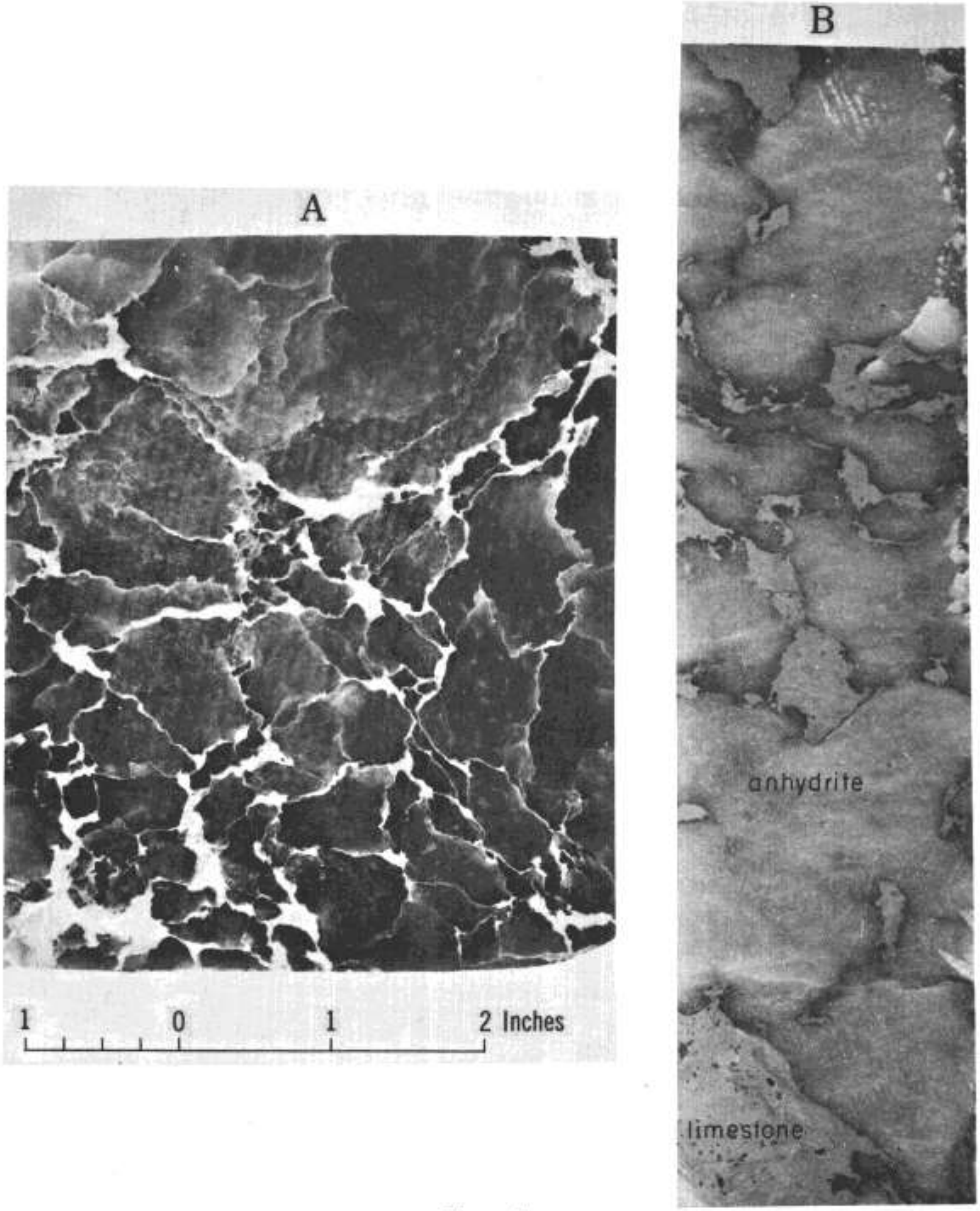

Figure 5

PHOTOGRAPH OF ANHYDRITE FROM THE ST. LOUIS LIMESTONE, MARTIN COUNTY, IND., HAVING MOSAIC TEXTURE (A) AND ANHYDRITE FROM THE DETROIT RIVER FORMATION, LAPORTE COUNTY, IND., HAVING PENEMOSAIC TEXTURE (B)

The interstices in the St. Louis anhydrite are filled with calcareous gypsiferous shale. The irregular masses in the Detroit River anhydrite are limestone. (From Rooney and French, 1968, fig. 5)

In the sample from the Mississippian deposits of southern Indiana, the nodular or mosaic texture is apparent. The nodular texture is less apparent in the sample from northern Indiana, but it probably has a similar origin.

But the origin of these deposits is mainly of academic interest. One of James Thurber's characters, a villian, makes the statement, "Each of us has his weakness and mine is being wicked." My weakness is being practical (which in academic circles is much the same thing as being wicked) and I shall return to maters of exploration that may interest you more.

The northern Indiana deposits have a sandwich geometry (fig. 6); that is, a layer of anhydrite is enclosed between two thin layers of gypsum, the latter probably formed by a movement of ground water through the overlying limestone and underlying dolomite.

These relationships are easily understood but, surprisingly enough, some gypsum producers write off this area on the basis that the gypsum beds were too thin and that, with 20 cores, the deposit had obviously been adequately tested. I am of the opinion that this deposit, if not all similar deposits, is rimmed on the updip edge by a band of gypsum as much as 20 feet thick and 1 mile wide, but generally about 10 feet thick and perhaps less than 1000 feet wide.

In Figure 7, I have sketched what I believe is the typical cross section of a commercial gypsum deposit in an area of moderate to high rainfall during recent time. Ground water moving through the overlying and underlying rock hydrates the upper and lower parts of a bed of anhydrite to produce gypsum. A thin bed, say less than 15 feet thick, may be completely altered in this manner, but along the outcrop or subcrop of a thick bed, water moving downdip first converts the anhydrite to gypsum and then dissolves the gypsum, leaving a breccia behind that is more permeable than the enclosing rocks. An equilibrium is established between hydration of anhydrite and solution of gypsum, creating a narrow gypsum front. Where water is concentrated, by anomalous structure for example, a wider front or downdip deposit may develop. If this interpretation is correct, the Fish Lake deposit cannot be considered adequately explored until cores are taken around its updip margin.

The LaPorte deposit does support this interpretation because complete hydration has taken place on the northern part of the updip margin and the boundary between possible complete hydration in Survey Drill Hole 121 and surficial hydration in Survey Drill Hole 125 is sharp (fig. 8). But the data here are not conclusive, and judgment should be withheld until more cores are taken.

What I have described are deposits of gypsum and anhydrite centrally located in the United States, close to markets, and documented by more information than most new deposits not explored by the gypsum industry. Furthermore, gas and railroad lines pass through the area, and mining of limestone or dolomite alone, which must be imported into this part of Indiana, could pay much of the cost of mining gypsum.

Why, then, has there been so little interest? Part of the reason is the Clem Kadiddlehoppers in the industrial minerals industry.

Admittedly, the only article published on these deposits received a quick and honorable burial in the tombs of A.I.M.E. Transactions, but the discovery was announced in the newspapers, including the *Wall Street Journal* and the *New York Times,* and the deposit was described in a session devoted exculsively to gypsum at a national A.I.M.E. meeting.

What surprised me was the lack of response from the gypsum companies—not that I expected a dozen companies to jump into LaPorte County overnight leasing, but I did expect every chief geologist working for a gypsum company in the United States to request all the information readily obtainable about this significant new deposit so that he could help his management decide on options should his company ever decide to expand into the Chicago area. Gypsum geologists certainly should be on top of their field. After all, how many really new gypsum deposits have been discovered in this country during the last 15 years? Perhaps two or three. But very few companies looked at the cores or even got in touch with us. In fact, gypsum-company representatives still come to us with inquiries about the deposits in southern Indiana and are not aware of these deposits in northern Indiana.

My reason for citing these examples is to point out why good geologists are needed in industrial minerals and how they can contribute. The need is real and born of events and not the imaginations of university curriculum committees. It is born of the spectacular growth in production of industrial minerals and their inevitable conflict with urban centers.

A sign of this need was the organization some four years ago of the Forum on Geology of Industrial Minerals that has met successively in Ohio, Indiana, Kansas, and Texas and that will meet in Pennsylvania, Michigan, and Florida in the next three years. The Forum has been carried forward by the momentum of enthusiasm and not formal organization (by contrast, A.I.M.E. and A.A.P.G.'s paid staffs are so autonomous that they will be holding conventions five years after the last member has died). About 55 percent of the Forum participants have come from industry, 30 percent from government, and only 15 percent from universities and nonprofit research laboratories, even though all meetings have been held on or adjacent to college campuses.

Which brings me to the final point of my talk: the education of the geologist in industrial minerals.

In talking with company geologists who call on us for help, in appraising candidates for positions as industrial minerals geologists, and in reviewing the accomplishments of the men who have been working with me for the past five years, I have been impressed that a geologist in this field needs to have a broad training to better appraise the value of statistical, geochemical, geophysical, paleontological, or other approaches to a problem; that he be

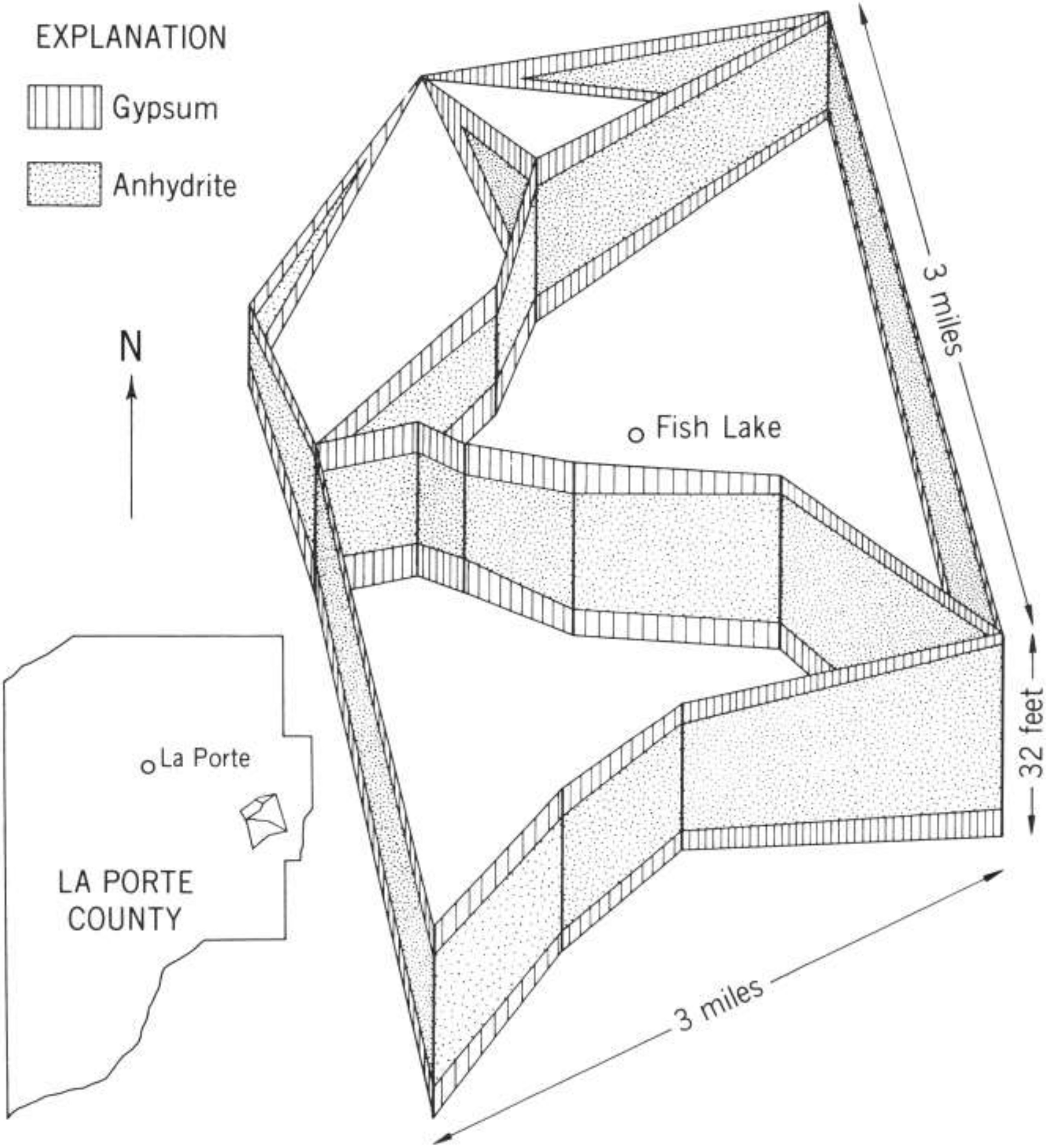

Figure 6
Fence diagram showing relative thickness of Gypsum and Anhydrite in the Fish Lake Deposit, Laporte County, Indiana
(From Rooney, 1965, fig. 6)

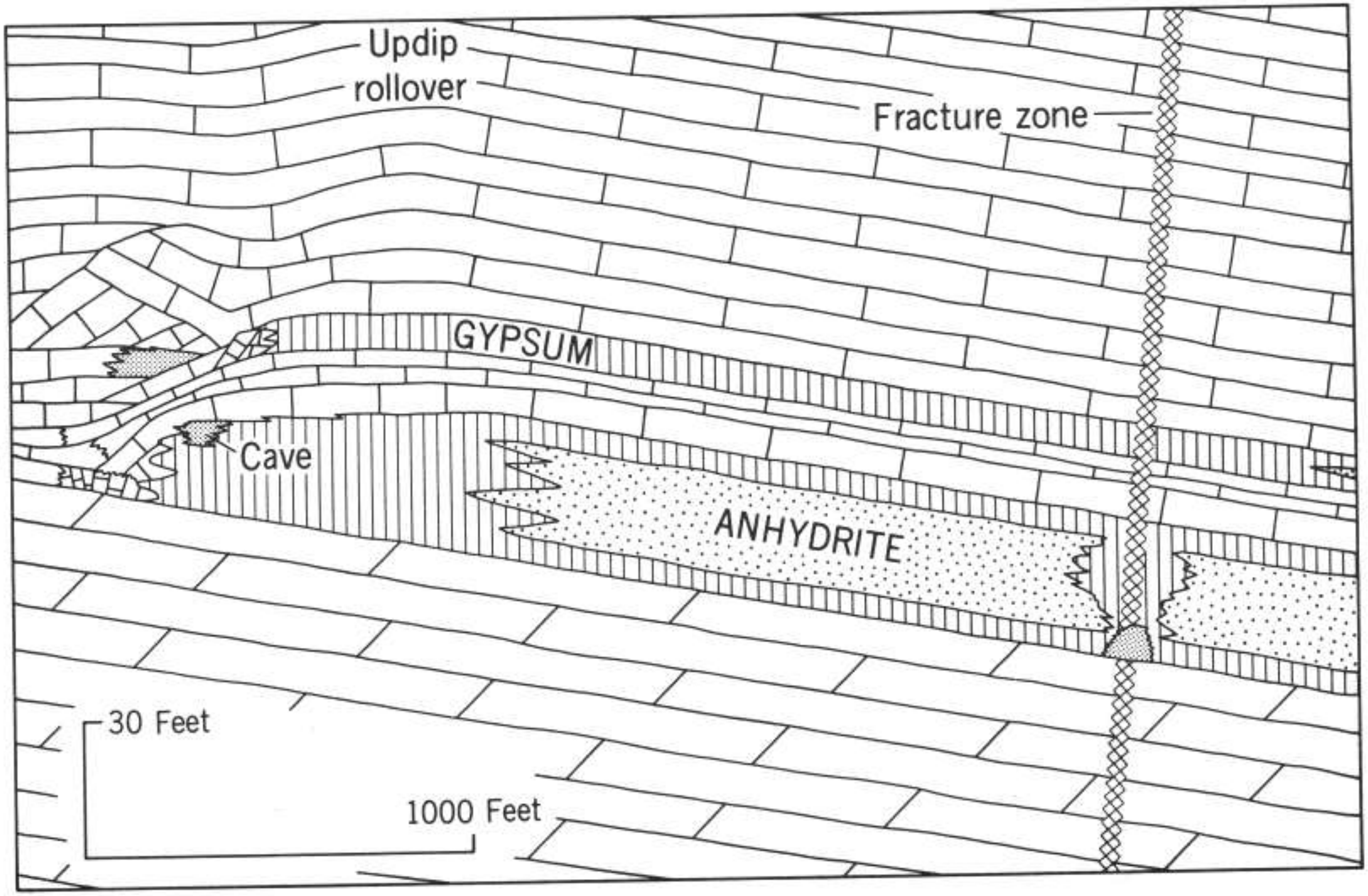

Figure 7
SCHEMATIC CROSS SECTION ILLUSTRATING ORIGIN OF GYPSUM DEPOSITS BY HYDRATION

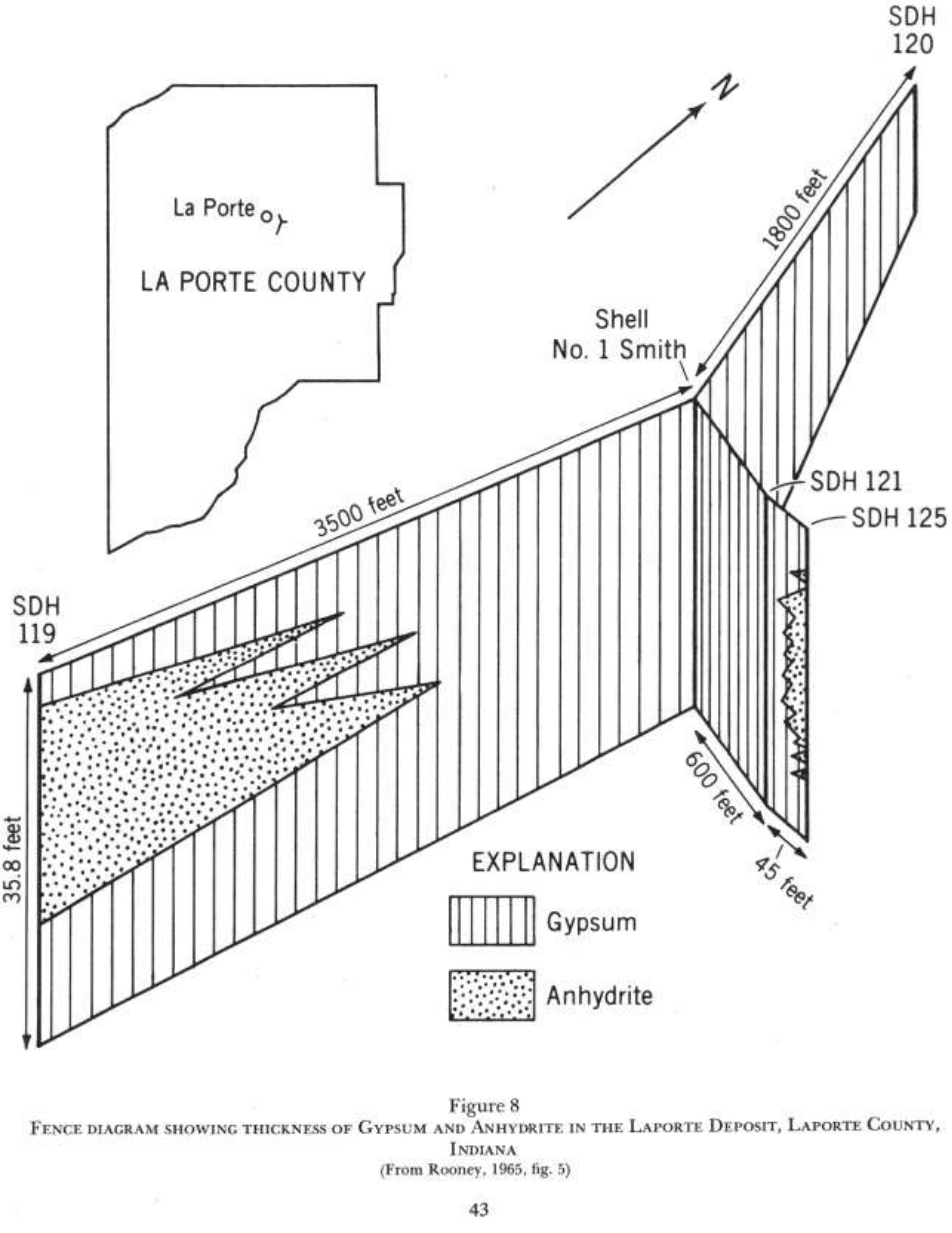

Figure 8
FENCE DIAGRAM SHOWING THICKNESS OF GYPSUM AND ANHYDRITE IN THE LAPORTE DEPOSIT, LAPORTE COUNTY, INDIANA
(From Rooney, 1965, fig. 5)

intelligent and have good judgment as to what is more or less important, what is relevant and irrelevant, and what can be and cannot be accomplished in a given amount of time; and that he not have been brainwashed into considering academic pursuits, the use of expensive equipment, and arcane jargon as more intellectual and worthwhile than applied and apparently simpler pursuits.

For example, stratigraphy is one of the most important tools for a geologist in industrial minerals but that part of stratigraphy bogged down in nomenclature only handicaps him. The rapt concern of the past ten years with capitalization and semantics appears to be nothing more than resurgence of medieval scholasticism, which seems to flower whenever significant goals are lacking.

Unfortunately, since many professors live in supersaturated solutions of their own egos—accretion, excretion, no matter, it is all the same divine stuff—the most gifted students are generally steered toward the Ph.D. degree and toward more and more specialization. In the past, most of them went into petroleum geology, where the money was; now they go into teaching, where the money is. Industrial mineral producers have been content to hire the B.A. and M.A. graduates, and, in most instances, this training is adequate for their needs, just as it is for the petroleum industry. But a large proportion of the geologists in industrial minerals are hired by state and federal agencies, and some noted geologists predict that more and more will be hired by the larger cities.

In these organizations, a Ph.D. degree makes a difference in salary; thus, the exceptionally bright M.A. graduate, who could be of every bit as much value to a government agency with an M.A. as he could with a Ph.D. degree, may feel driven to get a Ph.D. just to protect his future. But to satisfy his academic department, he is likely to be pushed into a narrow specialty and once in that narrow specialty, he is likely to find that teaching offers more financial and fringe benefits than industry or government. Thus, many of the brightest people are lost to the profession of applied geology. The only way I see to prevent this loss is more enlightened leadership in university geology departments and an emphasis on accomplishment rather than narrow expertise. And the only way that enlightenment can be achieved is by mineral producers and interested government agencies hiring their geologists from those schools that encourage applied geology.

And so to return to my question: Who killed Clem Kadiddlehopper? The answer is: Noboby has yet. But he is the certain victim of population and our society's gargantuan appetite for minerals and men of the highest quality to find them.

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Terradynamics

The Feasibility of Rapid Soil Investigations Using High-Speed, Earth-Penetrating Projectiles

by W. N. Caudle
Supervisor, Terradyamics Division
Sandia Laboratory, Albuquerque
A. Y. Pope
Director, Aero Projects
Sandia Laboratory, Albuquerque
R. L. McNeill
Director Special Projects Division Woodward—Clyde—Sherard & Associates
Oakland, California
and B. E. Margason
Project Manager, Special Projects Division
Woodward—Clyde—Sherard & Associates
Oakland, California

Techniques for soil investigations have not enjoyed any substantial changes for many decades. Recent efforts, particularly for large civil projects in remote areas, have shown that conventional techniques can be quite expensive, in time as well as money. This paper will explore the feasibility of a new study technique, the use of high-speed earth-penetrating projectiles for soil investigations.

Penetration of the earth and earth structures by projectiles has been investigated many times in the last two centuries. Robertson (1941) presented a good review of work done prior to World War II. Most of the work had a particular military application in mind, such as the penetration of earth revetments by cannon balls; however, little (it appears that none) of this past investigation concerned the scientific purpose of studying the earth-penetration phenomenon. A perusal of published results indicates that most work prior to about 1960 was of limited value for three main reasons: (1) The projectiles were of normal ballistic rather than earth-penetrating design, so that they tumbled and twisted during the penetration event; (2) the earth materials were usually unrealistic and none was ever described properly (for example, loam embankment, compacted sand); and (3) the projectiles were not instrumented, so that only entrance velocity, penetration depth, and projectile properties were known from the test.

In one notable instance a projectile was designed specifically for earth penetration, according to some German work summarized by Pope (1964). In the early 1940's, a German artillery group developed an 8-inch-diameter penetrating round that was fired in high trajectory from a cannon to impact the earth at about 1100 fps. The results were quite spectacular: At one target, the projectile penetrated 50 feet of "loose stone and clay" overburden, then 60 feet of "chalky marl" rock, and still had enough momentum left to perforate completely 2.5 feet of 10,000-psi reinforced concrete.

Scientific studies of large-scale earth-penetration events in natural soils were undertaken by Sandia Corporation in 1962. The Sandia program to date (June 1967) has involved a total of 692 earth-penetration events, of which 382 have been instrumented to record the deceleration experienced by the projectiles (Pope, personal communication, 1962; Pope and Caudle, personal communications, 1963; Caudle, personal communication (work by D. Laumbach, Sandia Corp.), 1964; Caudle et al., 1967; D. W. Doak, personal communication, 1966; Patterson, 1967; Pepper, Widdows, and Lucero, 1967; Schuster, 1964; L. J. Thompson and J. L. Colp, 1964; Thompson, 1966; P. R. Wilkes, unpublished data, Sandia Corp., 1966; Young, 1967).

The Sandia studies have been made in both soil and rock materials. Projectiles have successfully penetrated natural deposits of loose to dense moist sands, dense cemented sands and gravels, soft estuarine muds, stiff moist to saturated clays, hard dry silty clays, loessial permafrost, glacial ice, dense gypsite, and salt water; projectiles have also penetrated significantly into intact bedrock, such as dense sandstone, granite, welded tuff, and dacite. In most instances, the penetrated soil and rock materials have been carefully studied (Woodward—Clyde—Sherard & Associates, 1962-1967).

In the Sandia program, projectiles from 1 to 18 inches in diameter have been used. Penetrations approaching 100 feet in depth have been successfully accomplished, and depths of 200 to 300 feet in soil are possible, should they be required. The projectiles are usually dropped in free-fall from an aircraft or helicopter, as shown in Figure 1. In some instances, the aircraft may be dived to impart extra velocity to the projectile. Delivery of the projectile to the ground at the proper velocity is not really a problem; adaquate penetration can be achieved with a well-designed, aerodynamically stable projectile simply by tossing it out the door of a light aircraft.

Although the Sandia earth-penetration program is still under way, and a great deal remains to be learned, some

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Figure 1
HELICOPTER WITH SOIL PENETRATOR

important interim conclusions can be drawn from the effort to date. First, it is really quite easy to penetrate most soil and rock materials with a stable subsurface trajectory, if the projectile is designed specifically for earth penetration. Second, the penetration environment, expressed as deceleration, is surprisingly mild; usually only a few hundred g's are encountered in soils, but a few thousand g's may be generated in hard rock. Third, for a given projectile impacting vertically at a given velocity, the deceleration and depth depend on the properties of the soil and rock media being penetrated.

The first two conclusions mean that earth-penetrating projectiles and projectile systems can be designed for specific purposes. The third conclusion indicates that if the impact velocity and properties of the earth medium are known, the decelerations and depth of a given projectile can be predicted. More importantly, this also means that if the decelerations and depth are known for a given projectile and impact velocity, it is possible to determine the properties of the earth media penetrated.

The final conclusion suggests the use of earth-penetrating projectiles as a powerful investigative tool for subsurface studies and evaluations, a very attractive technique from a time and cost standpoint. Experience to date, however, indicates that the method still has minor limitations, as discussed below.

This paper discusses present knowledge of the phenomenology of earth penetration, the data obtained, interpretation of those data, design of the earth-penetrator system (delivery, data acquisition, and the like), and the presently apparent strong and weak points of the method.

EARTH-PENETRATION EVENT

The essential elements of an earth-penetrating projectile are shown in Figure 2. The device is usually solid metal, with a pointed nose. The afterbody is hollow to accommodate the instrument package and to provide a forward center of gravity. The aerodynamic fins on the tail provide stability while the projectile is falling through the air. These fins are made of a frangible material so that they shatter upon impact. The base of the aerodynamic fin is usually metal that protrudes perhaps 0.5 inch above the body; though small, the terradynamic fin seems to aid in maintaining stable underground trajectory. In addition, the ratio of vehicle length to diameter must be large, on the order of 8 to 10, for a stable underground trajectory.

In simplest form, the heart of the instrumentation is an accelerometer. The instrument package contains the accelerometer along with the necessary power and electronic amplifying and transmitting equipment to broadcast the accelerometer data. Data transmission travels through a long trailing-wire antenna attached to the instrument package and folded into the recess in the penetrator afterbody; it is pulled out by a small parachute activated when the projectile is thrown from the aircraft. The antenna must be somewhat longer than the expected penetration depth to make sure that the antenna will remain above the ground when the projectile comes to rest. To withstand the decelerations of penetration, the instrument package is carefully designed, always emcased in resilient plastic, and sometimes shock-isolated; it is the most expensive component of the projectile.

Figure 3 has been prepared to aid the following explanation of the earth-penetration event. As the projectile penetrates, Figure 3a through 3c, it continuously transmits its decelerations, which are received and recorded as a function of time, as shown in Figure 3d. When the free-falling projectile initially impacts the ground, the nose slices the soil (fig. 3a), causing a small crater to form with a minor amount of ejecta. At this time, the projectile has its maximum velocity, and the deceleration, shown by point (W) in Figure 3d, usually has a rather high value. As the projectile continues to penetrate, the aerodynamic fins shear off; this event can sometimes be seen as a small deceleration impulse.

When the projectile is well into the earth but still traveling at a reasonable velocity, penetration takes place mostly by the slicing action of the nose, interval (X) in Figure 3d. This slicing action shears and compresses a thin zone of soil around the projectile, pushing the soil particles away from the passing nose with considerable lateral velocity. During the intermediate part of the penetration event, this imparted lateral velocity moves the soil particles away from the projectile body; at all but the lowest of velocities, the body has moved past before the soil particles commence to rebound. Thus, there is little skin friction acting on the projectile body during the major part of the penetration event; as a rule, the paint on the penetrator afterbody is only slightly scratched. The soil particles do, however, rebound somewhat after the projectile has passed; the resulting trajectory hole is typically smaller than the projectile that made it.

The preceding explanation establishes that the main force system that resists penetration exists at the penetrator nose. This is a potential instability: The center of pressure, which is somewhere in the nose area, lies forward of the center of gravity, which is somewhere in the body. If the center of pressure moves off the projectile axis, the instability is mobilized. This is why short projectiles tumble and travel on erratic trajectories in earth materials. An efficient method to ensure stability is to make the projectile long in relation to its diameter, so that an incipient tumble can be resisted by lateral afterbody forces that would be mobilized. For this reason, present earth-penetrators are long, slender, smooth projectiles with efficient nose shapes.

As the projectile decelerates to near-zero velocity, the penetration phenomenon apparently changes. The lateral velocity imparted to the soil particles by the slowly moving nose is of small value, so that the particles do not move far, and the projectile is moving so slowly that it cannot pass a given point beofre the soil particles can rebound. Once this process starts, the penetration event is essentially over. The soil tightly grips the body of the projectile, greatly increasing the deceleration (point (Y) in fig. 3d), and the projectile is stopped. For many penetration events, the terminal deceleration shows the highest value of the entire

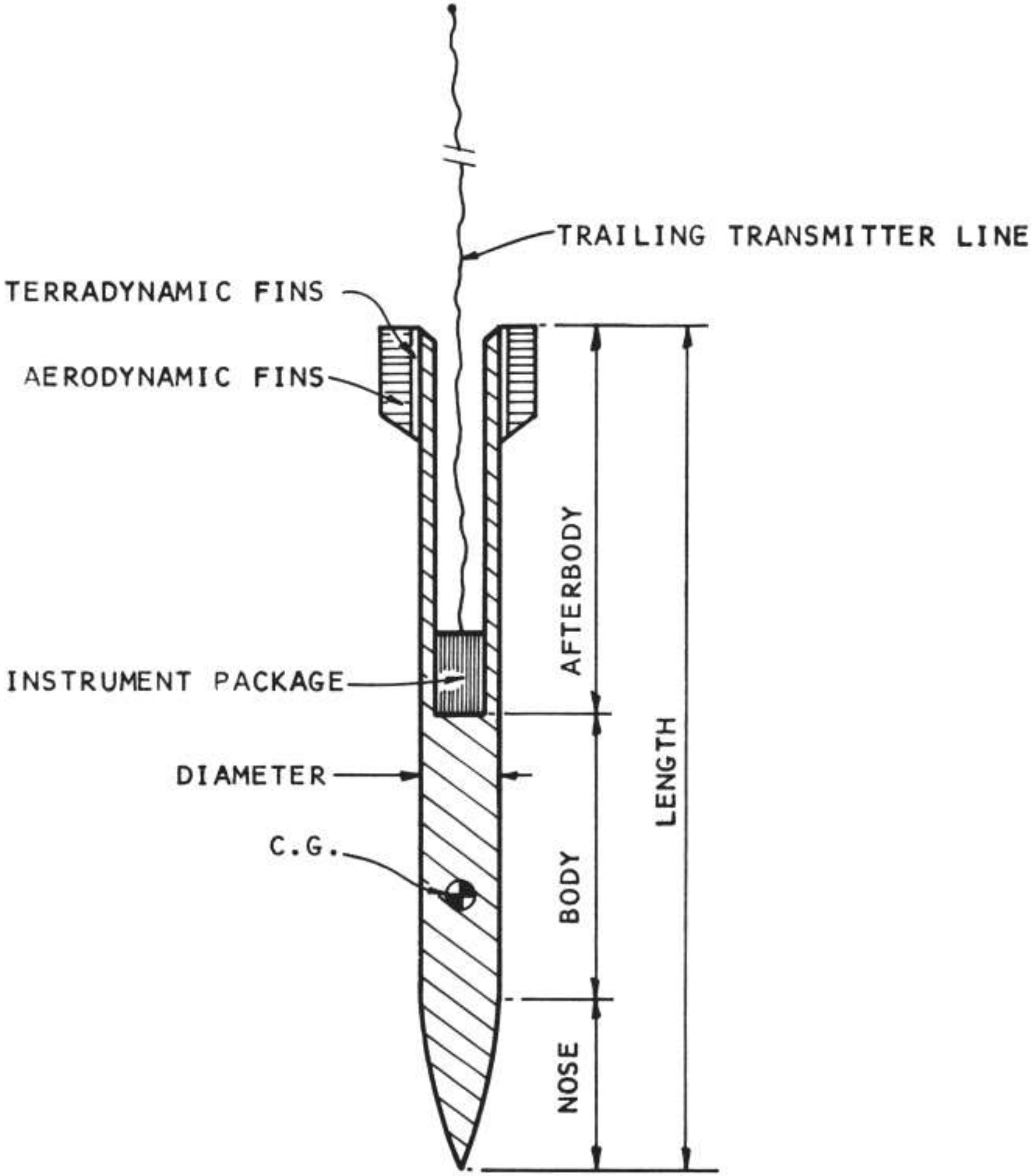
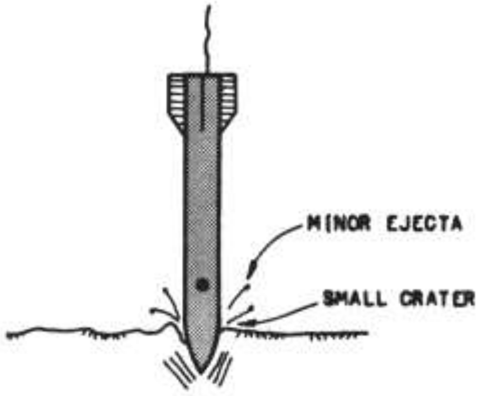
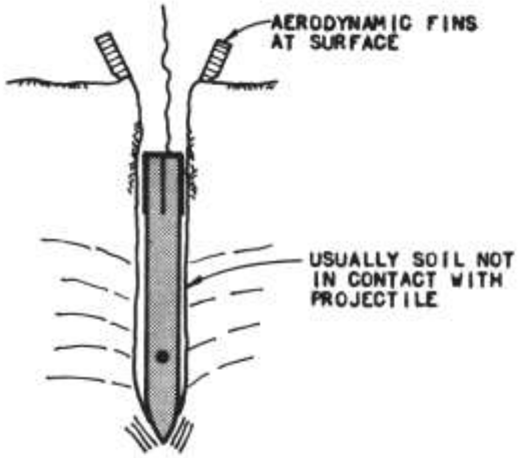


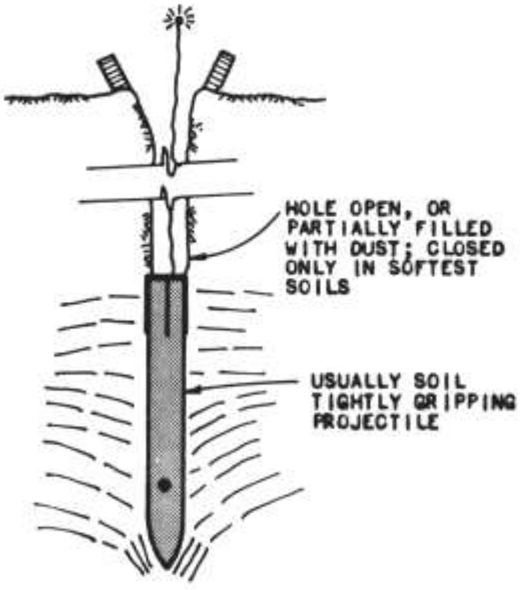
Figure 2
DETAILS OF EARTH-PENETRATING PROJECTILE



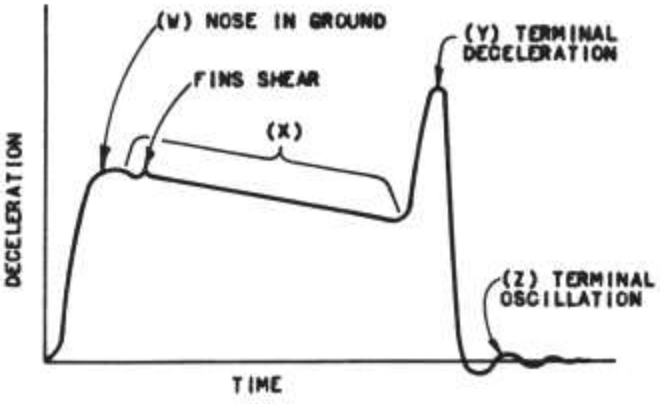
(a) INITIAL IMPACT



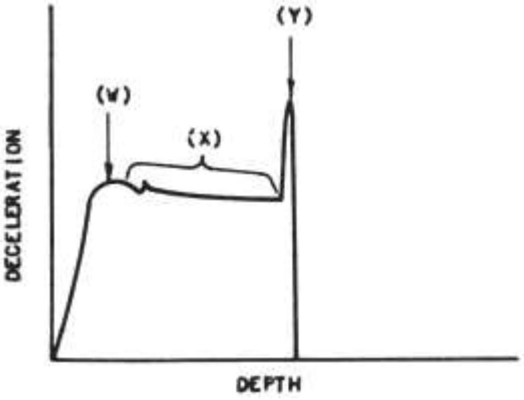
(b) DURING PENETRATION



(c) AT REST



(d) RAW DATA
PLOTTED AGAINST TIME



(e) DATA IN USEFUL FORM
PLOTTED AGAINST DEPTH

Figure 3
THE EARTH-PENETRATION EVENT
(Sketches, no scale)

record. After the projectile stops, the soil-projectile system often oscillates for a cycle or two, as shown at point (Z).

The data are most useful when deceleration is plotted as a function of depth (fig. 3e). This is accomplished by double-integrating the deceleration-time record and replotting the results. The main plateau is the most valuable part of the record because the decelerations in (X) depend on the properties of the material being penetrated. The terminal oscillation (Z) is also useful because it may be used to estimate the elastic properties of the earth medium in which the projectile comes to rest.

An example of the dependence of the decelerations on soil properties is shown by the data in Figure 4. The projectile in this instance was a 12-foot-long, 9-inch-diameter mild steel unit, similar to that shown in Figures 1 and 2. It weighed about 1160 pounds and was dropped from a helicopter to impact the ground vertically at a velocity of about 490 fps. The decelerations are shown as a function of depth in the left plot, and the soil profile, determined by drilling and sampling, is given on the right. This event took place at the northern edge of San Francisco Bay, in the well-known Bay Mud. The site is covered by about 4 feet of desiccated Bay Mud; the softer mud below extends to a depth of 72 feet. Below the mud is an 8-foot layer of medium dense sand that contains some clay. Below this lies an older and stronger Bay Mud which, at this location, contained an anomalous, 8-foot layer of medium dense silt at a depth of 92 feet.

As the projectile entered, passing through the desiccated surface crust, it felt the resistance of the initial desiccated zone, as shown by the high deceleration at point 1. Points 2 and 3 show where the fins sheared off, and point 4 indicates where the trailing antenna fouled momentarily in the collapsed hole (in this extremely soft material, the hole closed in behind the projectile). Points 2 through 4 should be ignored when interpreting for profile characteristics. The Bay Mud, although an underconsolidated deposit, does increase somewhat in strength with depth, and the projectile felt this increased strength, as shown by the gradual deceleration increase from 12 to 72 feet.

At 72 feet, the nose entered medium dense clayey sand, which is much harder than the mud. The projectile immediately felt the increase of hardness, as evidenced by the higher deceleration level from 72 to 80 feet. At 80 feet, the nose entered medium stiff clay, which is not so hard as the overlying sand, and the decelerations decreased. At 92 feet, the nose entered medium dense silt and punched through into stiff clay at 100 feet. In this silt-clay sequence from 92 to +100 feet, the decelerations should have decreased because these materials are not so hard as those above. The event terminated here, however, when the side friction of the soil started to act on the penetrator. For this reason, the decelerations are inordinately high at the end of the record.

In Figure 4, the layer interfaces are easily detected by the rapid changes in deceleration. Also, notice that the decelerations reflect the various soil strengths; in the mud down to 72 feet, the decelerations even reflect the gradual change in strength due to consolidation. Finally, notice that the over-all deceleration values in soft saturated materials of this sort are small.

Another interesting example is given in Figure 5. The projectile was similar to the one described for Figure 4, but this time the projectile was dropped from an aircraft and impacted the ground with a velocity of 955 fps. This soil was a natural deposit of sand, which typically had non-uniform properties both in plan and in profile. One measure of the strength of such sand deposits is the standard penetration test (Terzaghi and Peck, 1948), the results of which are tabulated on the right-hand side of the soil profile in Figure 5.

The near-surface sand is very loose. At about 10 feet, it grades from loose to medium dense, at about 15 feet. None of these variations is distinct, and the deceleration record in this zone does not show any distinct interfaces. If the material were of uniform strength, the decelerations should show some decrease because the velocity is decreasing. In this instance, the decelerations increase slightly and then remain constant. From this, one would deduce that the material is becoming stronger with depth, as is the case. At a depth of 30 to 35 feet, the material becomes much weaker, reflected by a distinct decrease in the decelerations. Curiously, even though the material becomes stronger at about 50 feet, the deceleration record fails to show an appreciable increase. Finally, at a depth of 71 feet, the projectile has slowed so that the soil can seize it, and the final deceleration peak is quite high.

These two examples (figs. 4 and 5) were chosen to illustrate that material properties, particularly strength, determine the decelerations experienced by an earth-penetrating projectile. There are, of course, other factors that influence the value of the decelerations. Some of these are impact velocity, projectile diameter and weight, nose shape, and the angle at which the projectile strikes the ground. Each of these factors will now be discussed briefly.

For a given projectile, the greater the impact velocity, the greater the penetration and the greater the decelerations. The effects are not linear, however. At high velocities, a given increase in velocity will cause a smaller increase in penetration than would the same given increase at a lower velocity. The kinematics of the last statement lead one to suspect that the opposite trends may be true for decelerations; that is, at high velocities, a given increase in velocity may cause a larger increase in deceleration than would the same increase at a lower velocity. This point is not presently clear, however, and is under study because of its implications to the design of the instrument packages.

The projectile size and weight affect the phenomenon according to the resulting *frontal loading,* defined as the penetrator weight divided by its projected frontal area. For projectiles of the same diameter, impacting at the same velocity, a larger frontal loading (greater weight) yields more penetration and lower decelerations. Similarly, a sharper (more efficient) nose shape allows the penetrator to slice more cleanly into the soil, yielding more penetration and smaller deceleration. These observations are used to design projectiles that, for a desired penetration path, yield decelerations in a desired range.

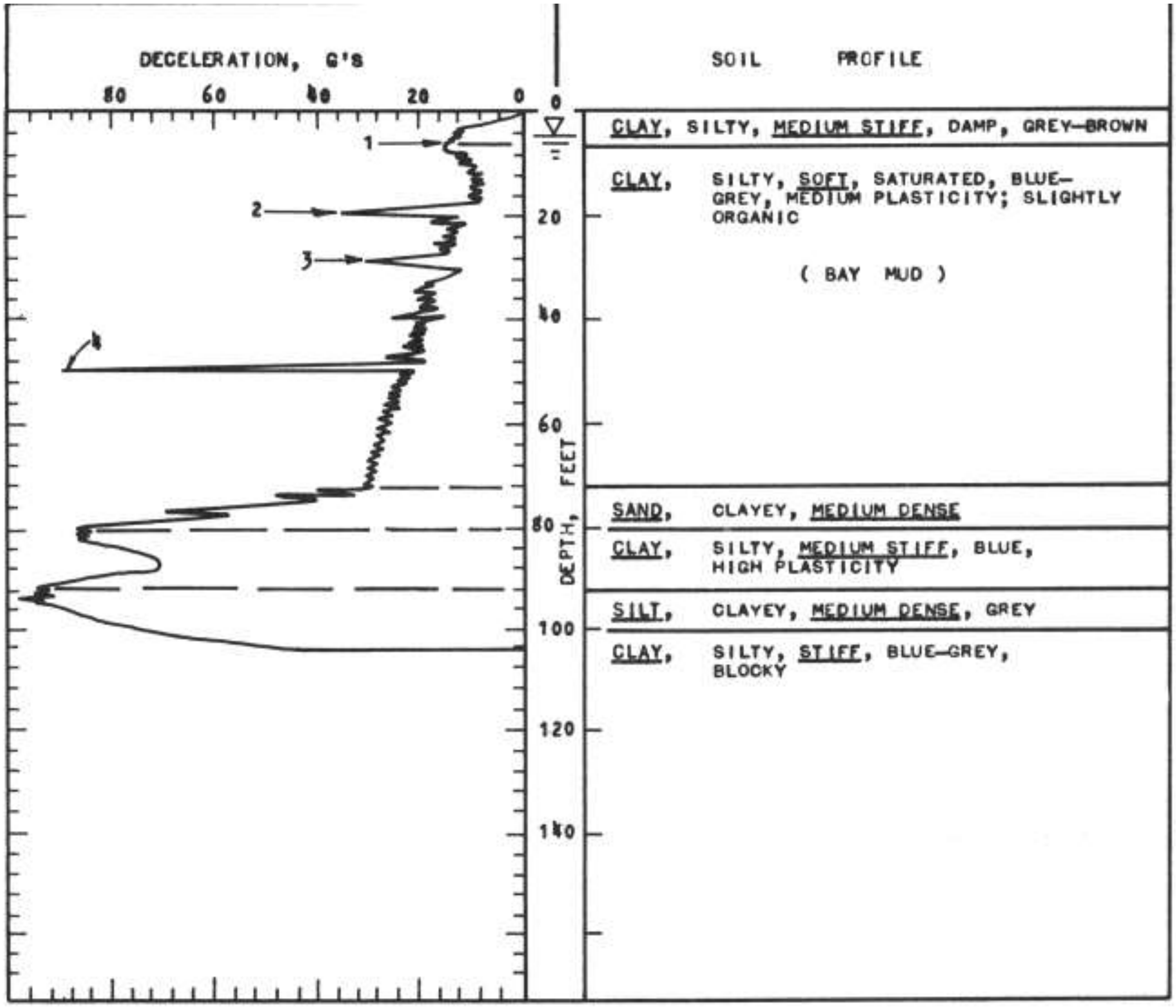


Figure 4
PENETRATION EVENT IN SATURATED SOILS

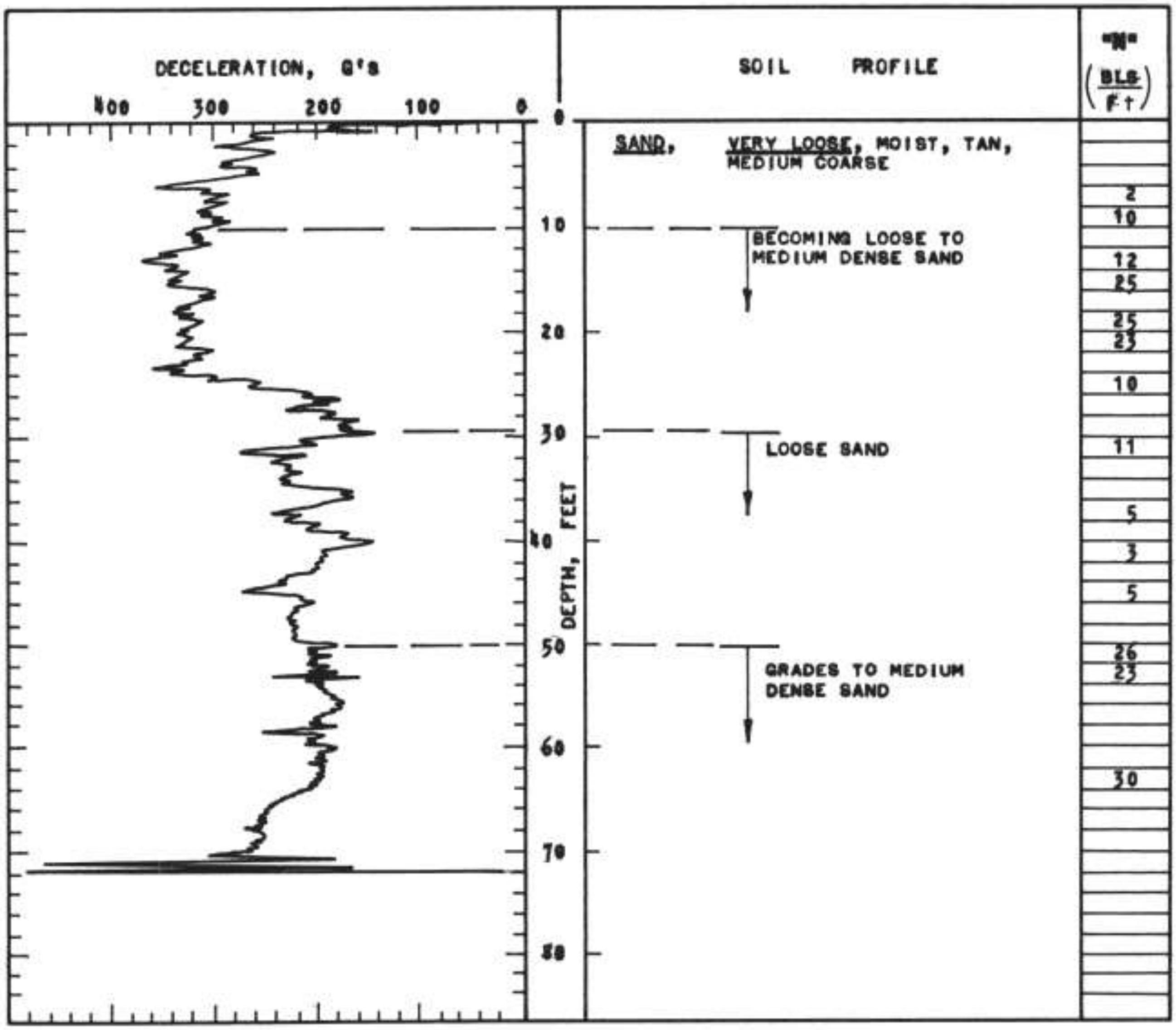


Figure 5
Penetration event in natural deposit of moist sand

If the projectile strikes at an angle other than normal to the target surface, several things can happen, depending on the *angle of attack*, defined as the angle between the velocity vector and the longitudinal axis of the projectile. If the angle of attack is not zero, the projectile is subjected to violent side forces and turning moments that are not completely understood. For this reason, every effort should be expended to assure that the angle of attack is essentially zero.

For zero angles of attack at large (nearly horizontal) impact angles, a projectile may *broach* (that is, enter the ground, travel a short distance, turn toward the surface, and re-enter the air). For zero angles of attack at small striking angles (nearly vertical), however, the projectile follows a straight, possibly inclined path, and is stable. Herewith, the inclined path length deviates from a vertical path length by a function of the sine of the striking angle. For practical problems of small striking angle, the resulting error is trivial. Thus, for an aerodynamically damped and stable projectile dropped on a calm day onto a sensibly flat surface, the striking angle is not important.

When these projectiles are to be used for subsurface investigation, it is necessary to minimize the sources of error and to maximize the sensitivity to soil properties. In general, the sensitivity to soil properties is greatest for relatively low frontal loadings (low weight), large diameters, moderately sharp noses, and intermediate impact velocities. There are some practical limitations to these comments; frontal loadings cannot be reduced too far or the resulting decelerations become excessive and nose sharpnesses cannot be reduced too far or the resulting spike at initial impact obscures valuable data. Present designs optimize such opposing effects.

PROJECTILE SYSTEM FOR SOIL INVESTIGATIONS

An investigation system using earth-penetrating projectiles consists of the following components: (1) the projectile; (2) the delivery system; (3) on-board instrument package; (4) receiving and recording facilities; and (5) data-reduction facilities.

The projectile must be light in weight so that one or two men carry it. A weight of about 100 pounds fits this requirement. The projectile is cut from a commercial billet of steel, usually 4 to 6 inches in diameter. The nose, in tangent ogive or cone shape, can be turned from a template. The afterbody is hollowed (fig. 2) to the size of the instrument package. The premade fins are screwed onto the afterbody.

For projectiles intended to penetrate hard rock, hardened steels must be used. A photograph of a hardened projectile successfuly used in rock is given in Figure 6. This rock was a calcareous sandstone with an average unconfined strength of 5500 psi.

A delivery system consists of a helicopter or light aircraft with a crude bombsight; a gimballed telescope is adequate for this purpose. One or two inert practice projectiles containing smoke spotting charges must first be dropped to ensure hitting the desired location. Having established the proper release times, the projectiles may then be manually dropped as indicated by the bombsight. This simple delivery system is attractive for remote locations; however, for accessible locations, a truck- or tractor-mounted recoilless rifle delivery could be designed.

The only on-board sensing instrument required is the accelerometer, although other instruments are desirable for special problems. The instrument package contains the required power, amplifiers, and transmitter. The design of the instrument system is well understood as a result of the Sandia development effort; however, the cost of the instrument package needs to be minimized.

The receiving and recording facilities can be carried in the drop aircraft. If desired, a higher power sender or relay in the aircraft could be used to boost the signal and send it to a ground receiver and recorder station. Such a station could also include the data-reduction facility.

Two sequences of data reduction are required: (1) double integration to yield the deceleration-depth curve (fig. 3e) and (2) experienced analysis of the deceleration-depth curve to deduce the soil properties. The problem of analyzing the integrated data to deduce soil properties is still being studied; as further information becomes available, it will be published. However, some qualitative analyses now exist to indicate the uses and limitations of these, techniques. First, however, a summary discussion of the system will be given.

Figure 7 shows the sequence of events in a site profile investigation using earth-penetrating projectiles. The sketch at the top of the figure shows an assumed actual profile as, for example, might exist at the proposed alignment for a dam in a remote location. An aircraft equipped with the receiving and recording equipment is shown flying the alignment and dropping the projectiles. Five units are shown, each in a different stage of the event. Unit 1 has penetrated to its full depth and has stopped; Unit 2 is still penetrating and is still broadcasting the decelerations it experiences; Unit 3 is shown in free fall, acquiring velocity under the acceleration of gravity; Unit 4 is shown as it starts to stabilize aerodynamically and as its trailing antenna starts to deploy; and Unit 5 is shown just as it is released from the aircraft.

For the profile shown, the deceleration-depth records would be as given in the middle sketch of Figure 7. Unit 1 would experience severe and highly varying decelerations as it penetrated the dense gravel and talus deposit. That material, noted on the lower sketch of Figure 7 as material A, would be identified as dense because of the high value of the decelerations and as either large-grained or highly erratic because of the large variations in deceleration. Upon entering the medium dense sand, Unit 1 would experience moderately high decelerations, and the record would show the mild variations, similar to electronic noise but at a much lower frequency, that are diagnostic of sandy deposits. That material, noted as material B on the figure, would be identified as medium dense to dense because of the value of the deceleration, as granular, even sandy, because of the mild hackles on the record, and as uniform

Figure 6
TYPICAL PROJECTILE AFTER PENETRATION INTO TRES HERMANOS SANDSTONE; RECOVERY IN PROGRESS

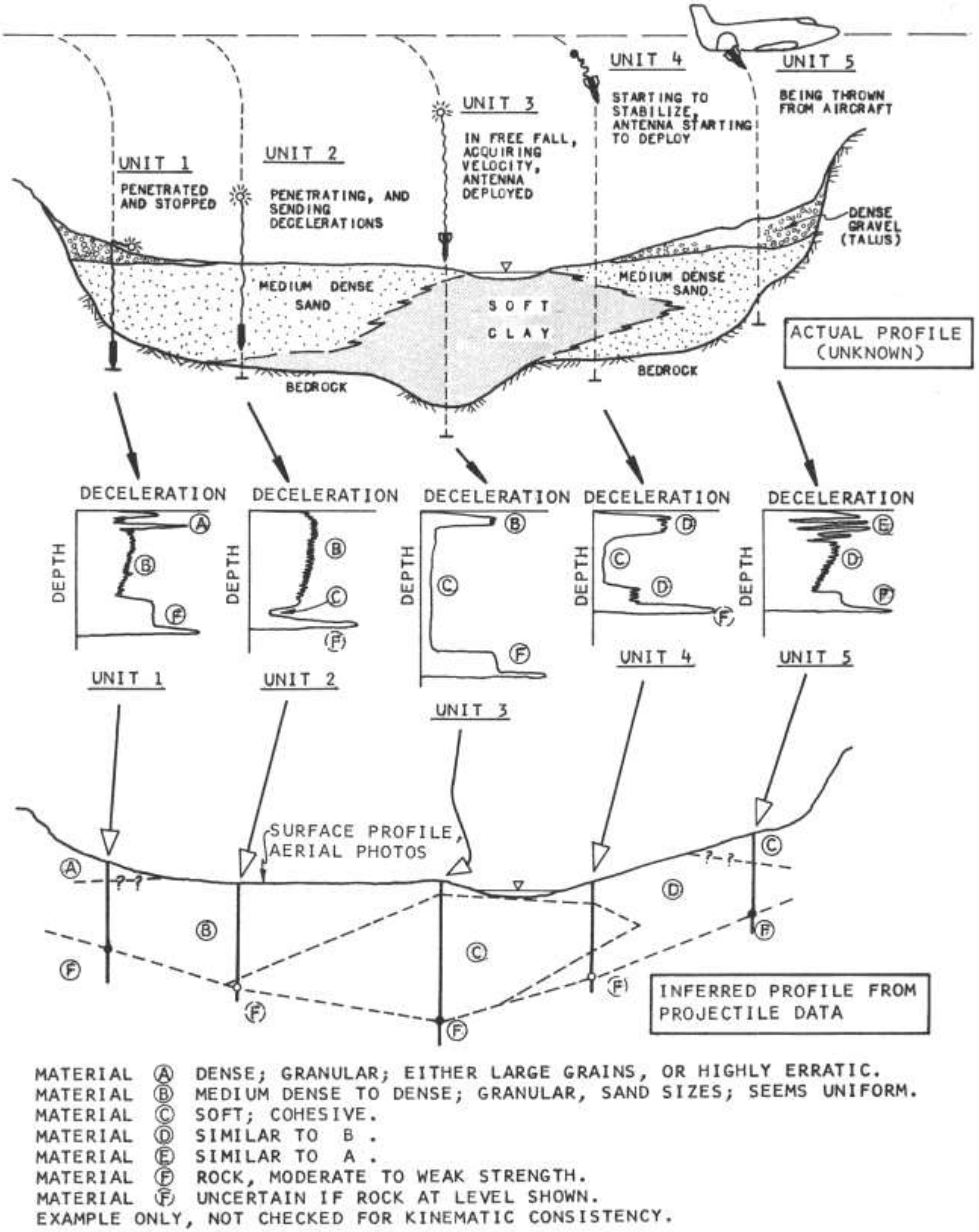


Figure 7
EXAMPLE OF SOIL INVESTIGATION USING HIGH-SPEED PROJECTILES

because there are no pronounced or large variations of deceleration. Upon entering the underlying bedrock, Unit 1 would experience a pronounced increase in deceleration, as shown in the figure, with the very high terminal value as the projectile is seized by the medium. That material, noted as material F on the figure, might be identified as a rock of moderate to weak strength. However, from the relative values of deceleration on the deceleration depth curve shown in Figure 7, it would be difficult to ascertain from this single record whether the material was a very competent soil or a moderate to weak rock. This same uncertainty often exists in conventional investigations of sedimentary rocks underlying competent soils. By comparison to the other records, however, one could observe the apparent uniformity of the decelerations, and, if the general geology of the area indicated the probability of such sedimentary rocks, the preliminary bedrock conclusion would be justified. If the presence of rock were a critical factor in the study, then a second run at higher velocities (higher drop altitude) would be made to penetrate farther into the suspected rock material.

Unit 2 (fig. 7) would experience moderately high decelerations with minor variations on the record in the upper medium dense sand; by comparison to the nearby Unit 1 results, that material would be identified as B. When Unit 2 passed through the soft clay, the deceleration level would drop appreciably before the very high terminal deceleration upon contact with the rock, where the unit is stopped with little penetration. The identification of materials B and C would follow from comparison to the records of the other units. The identification of the bottom material as F would, however, be somewhat uncertain; the high terminal deceleration shown could just as well have occurred if some more material B underlay material C. The data for Unit 4 in Figure 7 show this situation, with the uncertainty indicated. Such uncertainties exist for the general situation of a moderately strong soil overlying a moderately weak rock. In this instance, the projectiles should be impacted with enough velocity to carry them well into the rock. If the underlying rock is strong, then identification of the rock surface is much more certain. In fact, if weak soils overlie any rock or if strong rock underlies any soil, then the projectile technique is a very reliable method of determining the depth of the bedrock surface.

For example, Figure 8 shows the record that might be obtained from an offshore probe to determine the depth to rock and to identify the materials overlying the rock. Experience shows that, just as with conventional methods, it may be difficult to identify the upper boundary of the soft clay, especially if that boundary is a flocculated ooze.

The earth-penetrating projectile is also quite useful for detecting soft zones. For example, Figure 9 shows the results of a projectile penetration into permafrost. Several similar experimental penetrations in the same general locale had yielded decelerations on the order of 200 to 400 g's. The results shown in Figure 9 were, therefore, surprising because of the unexplained low decelerations in the zone from 4 to 8 feet. A subsequent boring program in this area showed an unfrozen and, in fact, soft and saturated zone from 3 to 8 or 9 feet, faithfully detected and reported by decelerations of the instrumented projectile.

SUMMARY AND CONCLUSIONS

Earth-penetrating projectiles and instruments have been in use successfully since 1962. Almost 700 penetrations have been accomplished by full-scale projectiles in natural soil deposits. The foregoing examples and records have been presented to show that the use of high-speed projectiles for subsurface investigations is feasible at the present time.

From the voluminous work to date, two important limitations have been identified: (1) The data are dynamic and (2) the engineer does not see and feel the earth materials. Thus, although the technique is extremely useful for feasibility studies or comparative explorations in remote areas, there is no presently sound basis for expecting that the technique should be used for final designs. Work is still under way, and techniques for the prediction of material strengths are being developed.

The strong points of the method are as follows: (1) One can identify material types, strong and weak materials, subsurface layer interfaces, and rock surfaces; (2) the data, because they are dynamic, are about as applicable to static design problems as the standard penetration test; and (3) the preliminary quantitative studies show good correlation with the standard penetration blow count (if velocity effects are accounted for). Finally, the method is most useful for preliminary soil investigations where ground access or time are problems. Examples of such situations include offshore studies, work in remote jungle or forested areas, exploration of incipient catastrophic failures such as large landslides in urban areas, and extraterrestrial exploration.

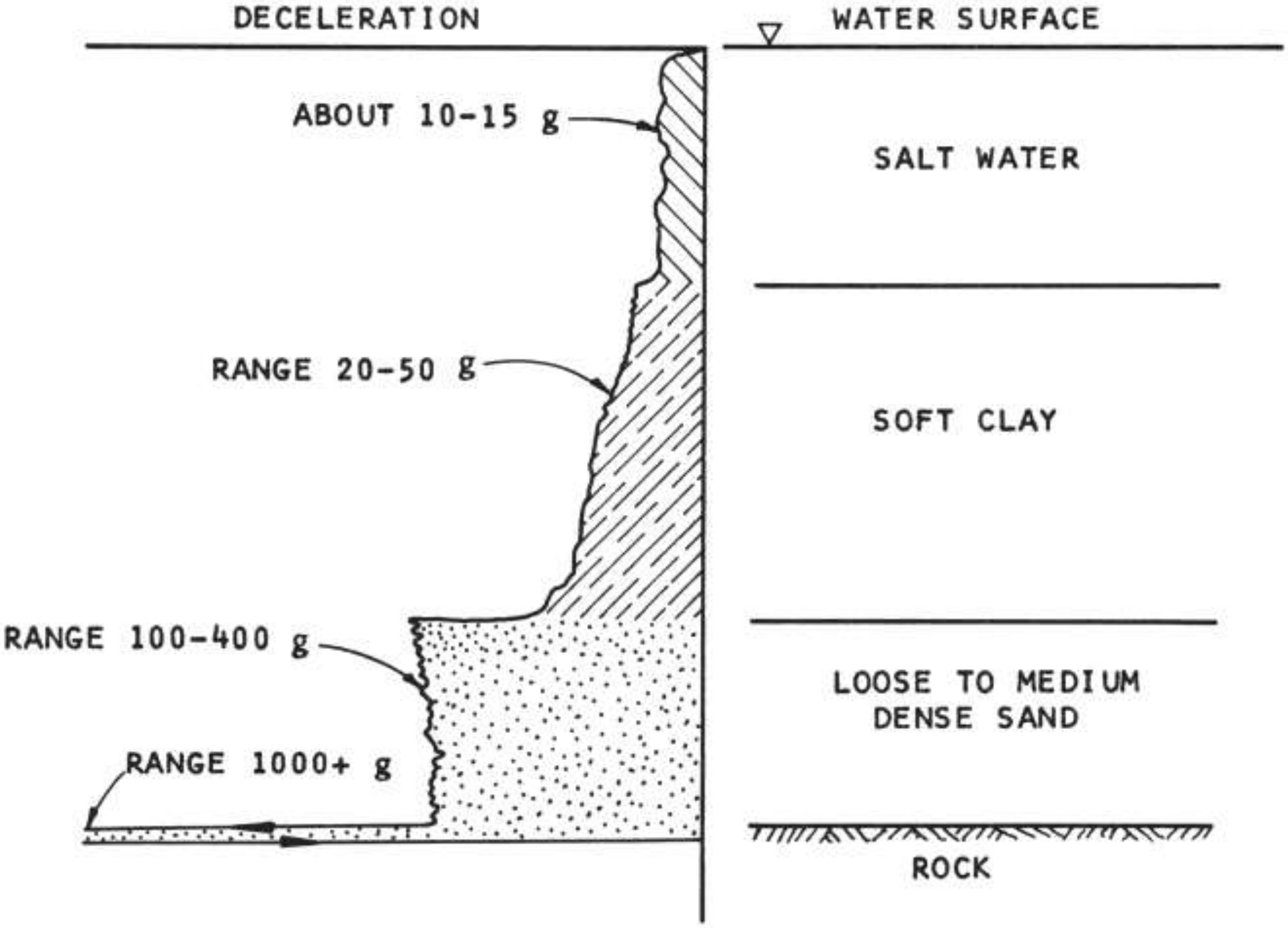


Figure 8
EXAMPLE OF OFFSHORE PROBE USING PROJECTILES
(Scale of record distorted for clarity.)

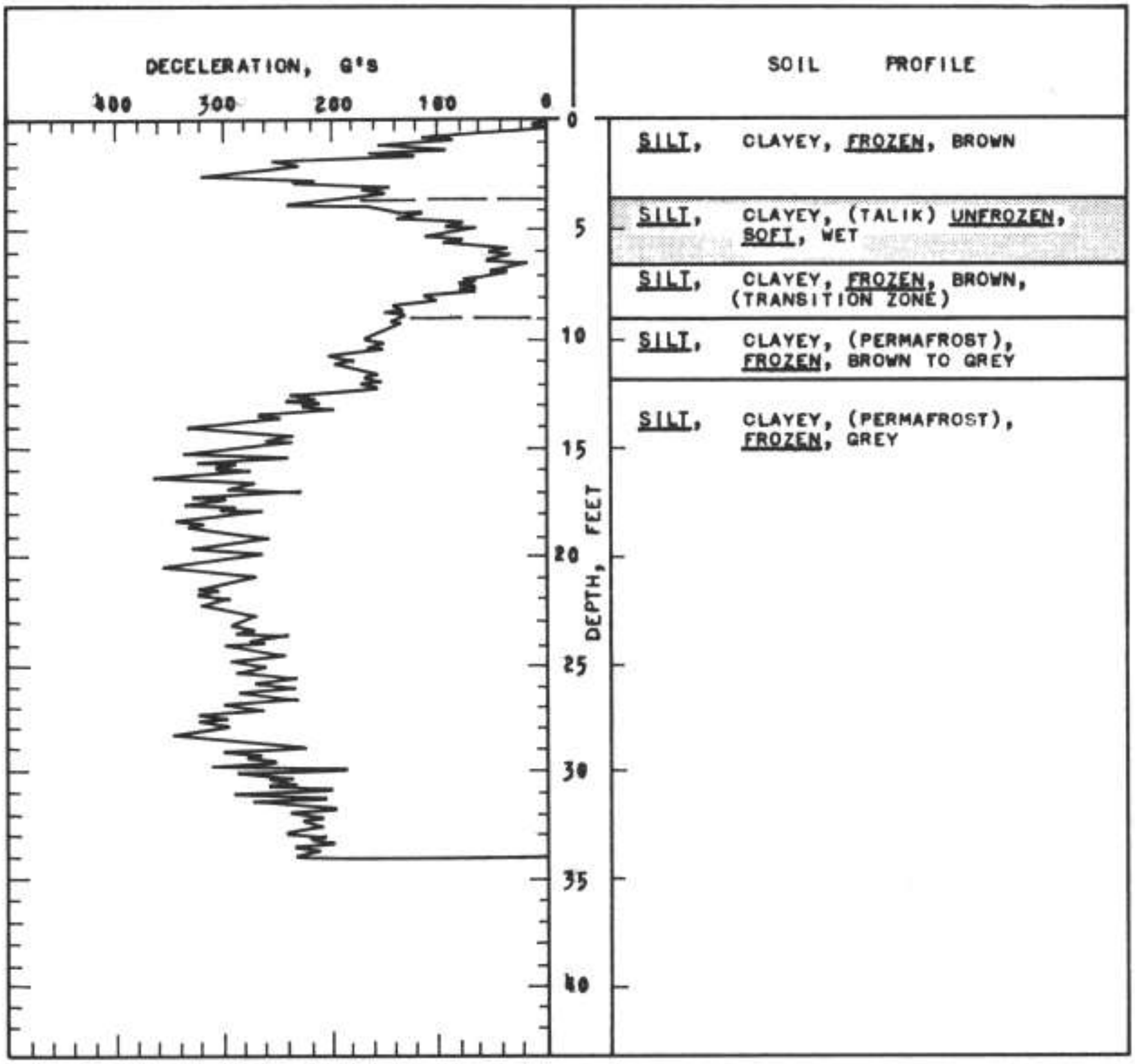


Figure 9
DETECTION OF A SOFT ZONE IN PERMAFROST

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Prospecting for Deeply Concealed Ore Bodies

by George V. Keller
Colorado School of Mines

The subject of prospecting for deeply concealed ore bodies is a very broad one, but this paper will be directed toward the rather narrow topic of the application of various electrical prospecting techniques to the problem. First, however, I should define what I mean by a deeply concealed ore body and explain why these kinds of bodies may be of interest economically.

A deeply concealed ore body is one that has been covered by a foreign overburden sometime after ore emplacement, so that the overburden reflects no primary or secondary indication of the presence of mineralization. This unrelated overburden makes the application of geological, geochemical, and geophysical exploration methods uncertain. The fact that most of the mines producing our present supplies of mineral commodities are located on or near outcrops of basement rock, where mineralization can be seen fairly directly in exploration, is a consequence of the difficulty in exploring through a foreign overburden. However, basement outcrop areas constitute only about 11 percent of the land area of the United States or only about 8 percent of the total area of the United States, including the related continental shelves, as indicated in the basement outcrop map (fig. 1A). The areas of basement outcrop include the Appalachian—New England province, the Rocky Mountain area, the Basin and Range province of the Southwest, and the Sierra Batholith of California. These areas also provide most of our mineral wealth, as is apparent from Figure 1B, which shows the locations of the 25 leading copper, zinc, and lead mines based on 1965 production as reported by the U.S. Bureau of Mines (1966). The coincidence between productive mining areas and basement outcrop areas is striking.

Large areas of rocks of the same type may be hidden beneath extensive volcanic beds of the western states. As indicated in Figure 2, nearly 10 percent of the land area of the United States is covered with Tertiary volcanic rocks. These may consist of basalt flows and related pyroclastics, as in the Columbia River Plateau area, or rhyolite flows and clastics, as in Nevada. In places, these volcanic deposits may have great thickness, in excess of 10,000 feet. Little is known about their thickness or what lies beneath them, in many areas. Crystalline basement rocks beneath a few hundred to a few thousand feet of such volcanic rocks would present an attractive area for prospecting. However, volcanic rocks are moderately conductive, having electrical resistivities ranging from a few tens of ohmmeters to a few hundred ohmmeters (Keller, 1960), and they have highly variable magnetic properties and density. A volcanic cover frequently confuses the responses to conventional geophysical prospecting tools.

An even larger part of the United States has the crystalline basement hidden beneath a few hundred to a few thousand feet of sedimentary cover, as shown in Figure 3. In the eastern half of the United States, these sediments are reasonably well known as the result of extensive drilling for oil or water. However, these wells rarely reach the basement complex, so it appears that almost a quarter of the land area of the United States where the basement is conceivably within reach of mining operations has not been tested for possible ore bodies. These areas covered by up to 2000 feet of sedimentary rock lie adjacent to the Precambrian shield in the Great Lakes area and east of the Appalachian folded belt, both major mineral-producing provinces.

In the western United States, the sediment-covered areas comprise those where Quaternary alluvium has filled the valleys between mountain ranges. The extent of these alluvium deposits is less well known, in view of their more complex stratigraphy. Alluvium thickness commonly ranges from a few hundred feet on the pediments of the mountain ranges to thousands of feet in the intermontane valleys. The thinly covered mountain flanks are an important exploration target, considering the mineral productivity of the exposed basement areas. The alluvial cover is sometimes a difficult problem in the application of geophysics. Its physical properties are highly variable, in view of the diverse rock types that may contribute to the alluvium. Both density and magnetic permeability can cover wide ranges, depending on whether the detrital material is volcanic, igneous, or sedimentary in origin. The electrical properties are particularly difficult to deal with, because the alluvial material commonly is saturated with brackish water that renders it moderately conductive. This conductivity makes penetration of electromagnetic energy difficult.

In some parts of the world, though not in our Southwest, other types of screening cover may overlie bedrock. On a worldwide basis, perhaps the two most important instances in terms of area covered are a continental shelf covered with sea water and an area covered with glacial ice. Because of the simplicity of the covering material, there is little interference with the use of gravity and magnetic methods in exploration, and in fact, such surveys are much easier to carry out at sea than in most other places. With electrical methods, the problem may be severe, inasmuch as sea water is so highly conductive that electromagnetic energy will not penetrate readily to the sea bottom, and ice is so resistant that methods based on the use of direct cur-

Figure 1a
OUTCROPS OF CRYSTALLINE ROCK IN THE CONTINENTAL UNITED STATES

Figure 1b
LOCATIONS OF THE 25 MINES PRODUCING THE MOST COPPER, ZINC, OR LEAD DURING 1965
(from figures compiled by the U.S. Bureau of Mines) Notice that fewer than 25 mines are indicated as lead producers; if a lead mine was also listed among the leading producers of zinc, only the order of importance with respect to zinc is indicated.

Figure 2

AREAS IN THE UNITED STATES COVERED BY TERTIARY VOLCANICS

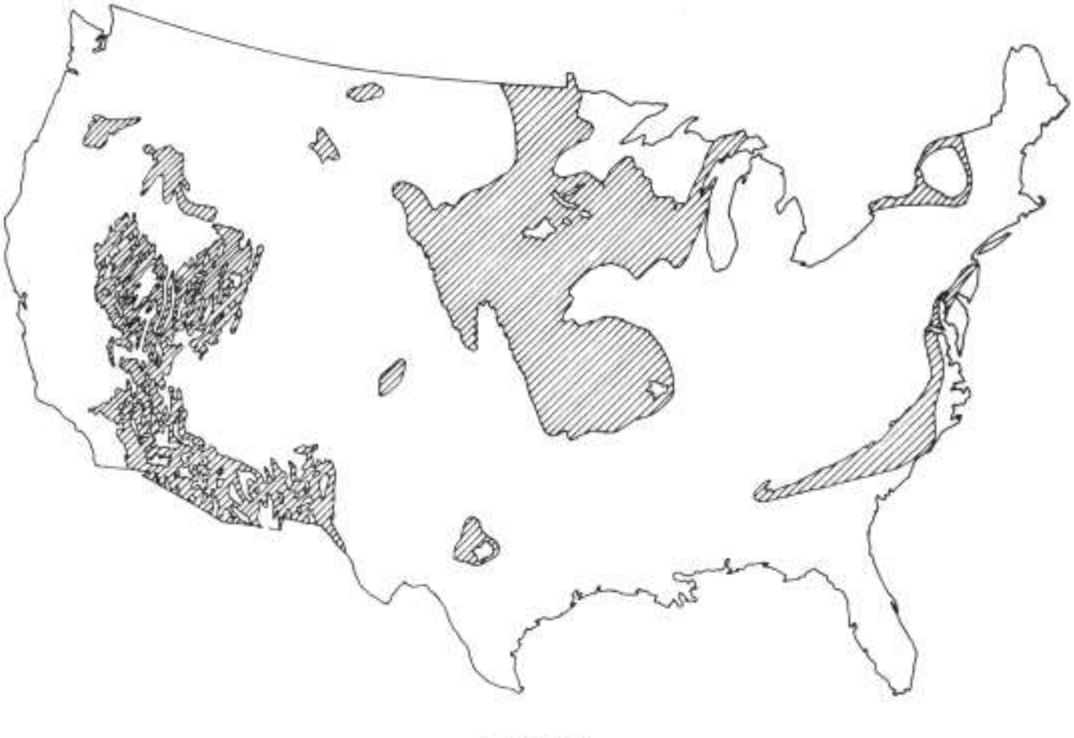

Figure 3

AREAS IN THE UNITED STATES WHERE THE CRYSTALLINE BASEMENT IS COVERED BY UP TO 2000 FEET OF SEDIMENTARY ROCKS (EAST OF THE ROCKIES) OR BY UNDETERMINED AMOUNTS OF QUATERNARY ALLUVIUM (WESTERN STATES) rent are practically impossible. However, let us restrict our attention to the first two types, those of alluvial or volcanic cover, which are more pertinent to exploration problems in the Southwest.

In considering how geophysics may be useful in the search for hidden ore bodies, let us review the experience we have gained in the application of mining geophysics over the past ten to fifteen years. Figure 4 is a graphical summary of the expenditures reported for several different mining geophysics techniques since 1954, based on yearly reports published in *Geophysics (see* Smith, 1966, for example). Based on the extent of expendiutures, apparently the successful methods belong to two groups: the magnetic method (and the gravity method, the figures for which are included here), where expenditures have been high but consistent over many years, and various electrical methods, where expenditures have been growing rapidly over the past few methods. The magnetic and the gravity methods have been recognized as effective exploration tools for several decades; the lack of an accelerated usage in recent years merely reflects that these are "mature" methods. On the other hand, electrical methods have been used effectively for a decade or less and appear not to have reached their full potential yet in the mining exploration picture. For this reason, I will conside; the electrical methods only as they may apply to the problem of prospecting for hidden ore bodies.

There are many different electrical prospecting methods, but in mining exploration, two general ones have been successful in recent years: the induced polarization method and the electromagnetic method. The induced polarization method has been reviewed in the volume on Mining Geophysics II, recently published by the Society of Exploration Geophysicists (Madden and Cantwell, 1967). Essentially, it consists of driving a current through the ground, using electrode contacts, and then measuring residual current flow after the excitation current is turned off. If metallic minerals are present in the earth, the excitation current causes corrosion of the grain surfaces and storage of energy in a manner similar to that in which energy is stored in a storage battery. The residual currents persisting after excitation may be quite large when measurements are made in mineralized ground.

With electromagnetic methods, the fact that a time-varying magnetic field will induce current flow in conductive material is used. In the usual approach, a time-varying magnetic field is generated by driving an oscillating current through a coil of wire. If the magnetic field from this coil cuts a conductive region, such as an ore body, currents are induced, and the secondary magnetic field generated by these induction currents can be measured. The electromagnetic method is very powerful because no direct contact need be made with the conductive region, so measurements may be made even from an airplane.

These, then, are the two classes of methods I will discuss as tools for use in the search for hidden ore bodies. It should be noted that reconnaissance becomes more important in the search for hidden ore bodies than for exploration on exposed surfaces. With the bedrock geology known from surface mapping, it is a simple matter to divide an exploration region into favorable and unfavorable areas, so that the expensive "detail" exploration methods need be applied only in locations where the probability of finding ore is reasonably high. The cost of the induced polarization and electromagnetic methods is sufficiently high, as they are now used, that regional reconnaissance is not practical. However, with hidden ore bodies, it is necessary to develop a reliable reconnaissance method that will localize targets worthy of expensive, detailed exploration. One possibility for reconnaissance is the use of high-altitude electromagnetic methods, discussed in the following section.

Once likely subcover targets have been located, they must be evaluated with detailed ground surveys. The cover interferes in two ways with the application of electrical geophysical methods: The object of exploration is further removed from the equipment than in exploration on an outcrop, so that relatively smaller effects may be observed, and the cover commonly contributes some response, which may be termed noise, to the method being used. Thus, in deep exploration, the anomaly to be mapped is smaller and is masked by larger random responses than in outcrop exploration. We will first consider the limitations to the use of induced polarization methods from the surface of the ground and then consider the use of "borehole-assisted" exploration methods as an approach to exploration beneath a thick cover. Usually boreholes are not drilled until the probability of finding ore is very high, but in this exploration problem, it may be more economic to drill holes to place exploration equipment in the target area than to attempt to deduce everything with surface-based exploration methods alone.

AIRBORNE ELECTROMAGNETIC METHOD

A variety of airborne electromagnetic systems has been used in mining exploration. These systems have been described in review articles by Pemberton (1962) and Ward (1967). The essential features of an airborne system are shown in Figure 5. An electromagnetic field is generated by passing a time-varying current through a source coil, usually mounted on the aircraft. The coil may havy either a vertical or a horizontal axis. The secondary magnetic field arising from eddy currents induced in the earth is detected with an induction coil, commonly in a "bird" towed behind and below the aircraft. In some instances, the receiver coil may be in a stinger in the airplane or carried by a second aircraft. The receiver coil may be oriented with its axis either vertical or horizontal, measuring the time-rate of change of the vertical or horizontal magnetic field.

The theory for how much field will be detected is very complex, even for a completely homogeneous earth. As a result, the development of airborne electromagnetic methods has been largely pragmatic, based on model studies and success or failure of techniques in use. Early model studies *(see* Hedstrom and Parasnis, 1959, for example) indicated that the secondary field decreased very rapidly with aircraft elevation, so airborne electromagnetic surveys

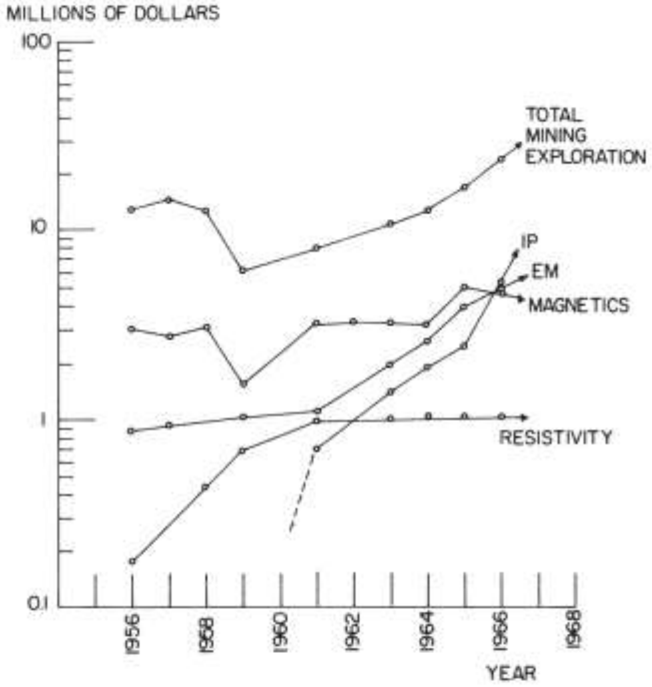

Figure 4
YEARLY EXPENDITURES ON VARIOUS FORMS OF MINING EXPLORATION
(as reported in *Geophysics* for the years from 1954 to 1966)

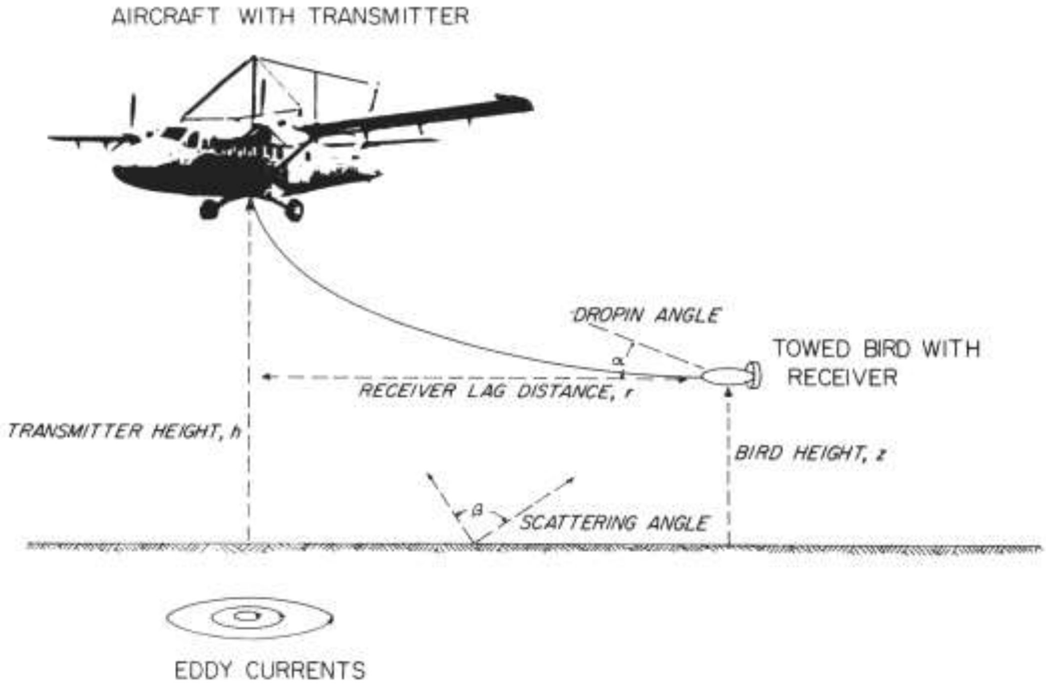

Figure 5
AN AIRBORNE ELECTROMAGNETIC SURVEYING SYSTEM
With the parameters used in theoretical analysis indicated

are flown at very low altitudes, generally under 500 feet. For full coverage, this means that profiles must be flown close together; therefore, the electromagnetic method is essentially a detail survey method.

For deep prospecting, there is some reason to believe that better results would be obtained at high flight elevations than at low elevations. The primary magnetic field from the transmitter coil varies in intensity as the inverse cube of the distance, neglecting propagation effects in the ground. Figure 6 shows the electromagnetic field density at the surface of the ground much higher than that at depth with a low-flying system merely because of the effect of geometric spreading of the field. The secondary currents induced in the ground are proportional in strength to the strength of the inducing field, as well as being dependent on the electrical properties of the ground. Thus, a low-flying system best sees the conductive material close to the surface. With a high-flying system, the geometric spreading is less severe and the relative excitation of eddy currents at depth is greater, if the field penetrates.

The second factor that must be considered in the use of electromagnetic measurements in exploration beneath a concealing cover is the matter of skin depth. An electromagnetic wave is attenuated by an amount that reduces its strength to one third in traveling a skin depth in distance. Inasmuch as the electromagnetic energy from an airborne system must travel down through the cover to cause eddy currents, and the secondary field from the eddy currents must travel back up through the cover, it is essential that the skin depth in the cover be much larger than the thickness of cover, at least several times larger. Skin depths are given as a function of frequency and resistivity in Figure 7. It is apparent from these curves that relatively low frequencies must be used to assure penetration of the cover, probably under 100 cycles a second.

Still another factor that must be considered is the response range for the airborne system: All airborne electromagnetic systems respond to relatively limited ranges of earth resistivity. There is some single value for earth resistivity that contributes a maximum signal to the system, with lesser signals being provided from rocks with either a higher or lower resistivity. This may be seen from a consideration of the theoretical response of the system, which may be evaluated using the extensive tables recently published by Frischknecht (1967). For an aircraft flying over a homogeneous earth, with the source coil being a vertical-axis coil and the receiver being a radial-axis coil (fig. 5), the magnetic field seen at the receiver is

$$H_{rad} = \frac{3M(z-h)}{4\pi r^4}\left\{1-\frac{1}{3}\left(\frac{\omega\mu\sigma r^2}{2}\right)^{3/2}\right.$$

$$\int g^2\,\frac{(g^2+z_1)^{1/2}-g}{(g^2+z_1)^{1/2}+g}\,e^{-g(z+h)\cdot\left(\frac{\omega\mu\sigma}{2}\right)^{1/2}}$$

$$\left.\cdot\;J_1\left[g\,r\left(\frac{\omega\mu\sigma}{2}\right)^{1/2}\right]dg\right\}$$

where M is the moment of the source coil (area times turns times current), r is the distance from the source coil to the receiver coil, w is the frequency in radians per second,o- is the conductivity (inverse resistivity) of the ground, m is 12.56 x 10^{-7}, and g is a dummy variable which diappears on evaluation of the integral.

The response for the airborne system may be calculated from this expression, but it is a tedious process even with a high-speed computer. Such computations have been carried out by Frischknecht, but for our purposes, the asymptotic behavior at low and high frequencies sheds more light on the problem. By assuming that frequency approaches zero or infinity, the integral in equation 1 reduces to a simple form and may be evaluated. Figure 8 shows the asymptotic response of this system. At low frequencies, the magnetic field does not depend on the properties of the ground but only on the height of the system, measured in skin depths. At high frequencies, the response varies linearly with the ground conductivity, as shown. Inasmuch as the time-derivative of the field is measured, rather than the field itself, the response recorded in flying is that shown in Figure 8, multiplied by frequency. This tilts the curves so that the maximum response is obtained near the intersection of the two asymptotes.

Another interesting property of these curves is the variation of the one asymptote with aircraft elevation. At low elevations, the field decreases very rapidly with increasing elevation, as shown by the inset in Figure 8. At some critical elevation, with (z+h)/r of about 1.5, the secondary field goes to zero, but with increasing height, the field recovers and then decreases more slowly. The rapid variation with altitude at low altitudes is the effect seen in early model studies, which has led to the use of low altitudes in practice. It appears from theory, then, that high-altitude flying may be feasible.

With an airborne system operated at several thousand. feet elevation and using a frequency of several tens of cycles a second, it may be possible to map resistivities in the range from 0.1 ohmmeter to 10 ohmmeters beneath volcanic or alluvial cover. This resistivity range coincides well with the resistivities expected in mineralized or altered basement rock; therefore, the method might be used to locate favorable areas for ore occurrence that can be studied in more detail with surface-based and drill-hole-assisted exploration methods.

INDUCED POLARIZATION METHOD

With the induced polarization method, the depth of investigation is determined by the spacing between electrodes. This distance must be two to ten times greater than the depth to be explored, with greater depths being required when the basement is more resistant than the cover. As greater electrode separations are used, larger and larger currents must be applied to the ground to get measurable signals. In present-day usage, power capacities of 10 kilowatts are common; with such power, measurements may be made with electrode separations up to one mile, provided the resistivity in the cover material is not too low.

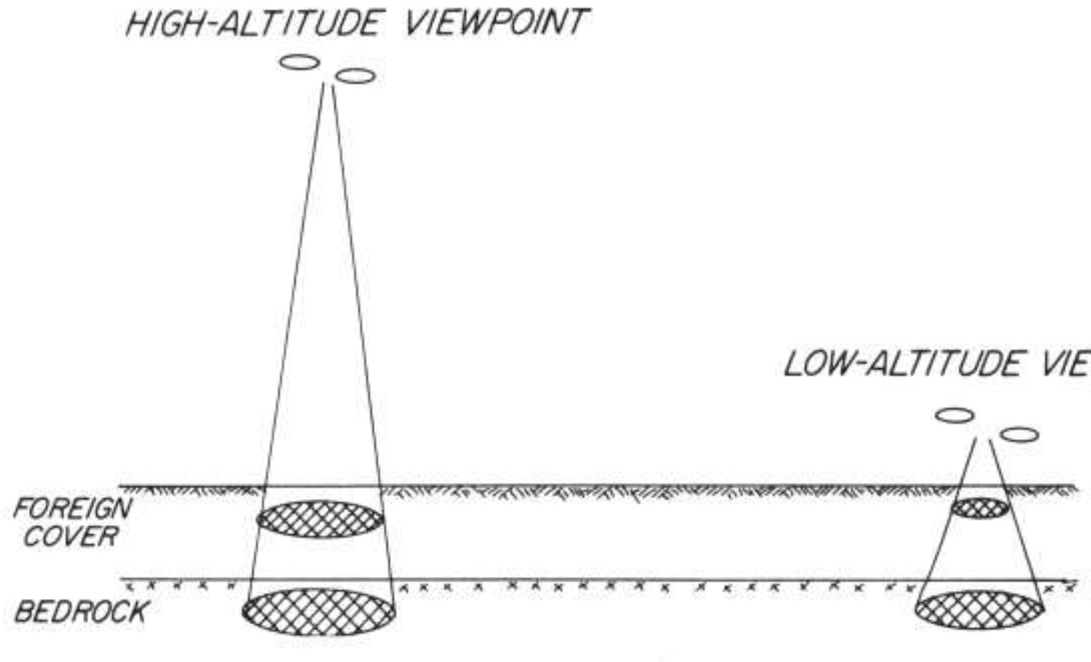

Figure 6
EFFECT OF ALTITUDE ON THE REDUCTION OF ELECTROMAGNETIC FIELD DENSITY BY GEOMETRIC SPREADING

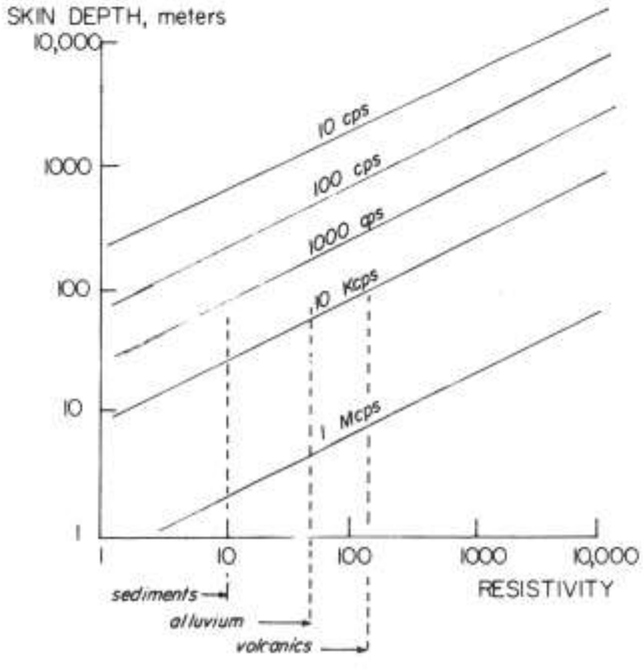

Figure 7
SKIN DEPTHS FOR ELECTROMAGNETIC WAVES AS A FUNCTION OF EARTH RESISTIVITY AND THE FREQUENCY USED IN PROSPECTING

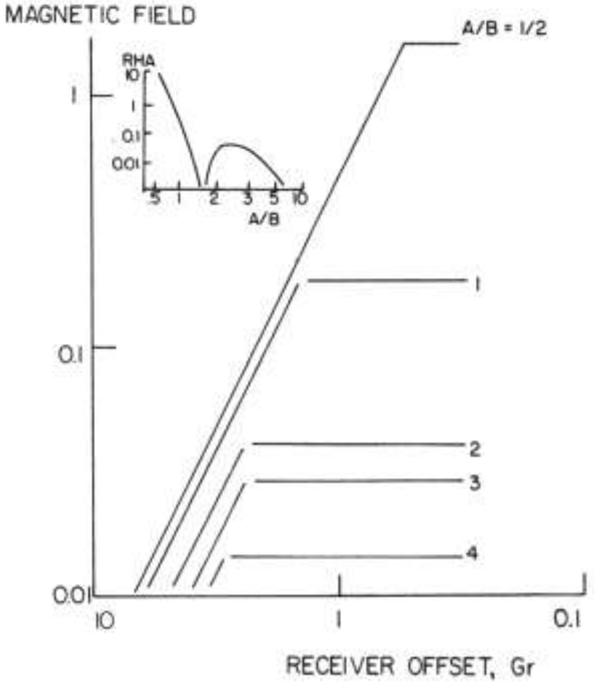

Figure 8
THEORETICAL ASYMPTOTIC RESPONSES OF AN AIRBORNE ELECTROMAGNETIC SURVEYING SYSTEM FOR LOW FREQUENCIES (TO THE LEFT) AND FOR HIGH FREQUENCIES (TO THE RIGHT)

The inset shows the magnitude of the right-hand asymptote (RHA) as a function of the ratio $B/A=(z+h)/r$, defined in Figure 5. The system considered is one with a vertical-axis induction coil source. The vertical magnetic field at the receiver is computed.

It appears that in order to explore through several thousand feet of cover, present-day equipment is very nearly adequate. However, even with the maximum spacings in use today, it is rarely possible to obtain highly reliable information at the maximum spacings because of problems with inductive coupling (Millett, 1967). When the excitation current is interrupted, a transient magnetic field is generated that will induce currents in the earth that may be confused with the residual currents caused by polarization of metallic minerals. This problem becomes more and more severe as the scale of the measurement is made larger and as the conductivity of the ground goes up. As with the airborne electromagnetic problem, the exact theory is tedious. For example, the electromagnetically induced voltage in a receiver dipole located over a uniform hut anistronic earth is given by the exnression

$$E_x = \frac{I\,dl\,\lambda\rho_1}{2\pi r^2}\left\{\left[3\lambda\alpha-\lambda\right]+i\,\frac{\omega\mu\sigma}{2}\left[3\alpha-\frac{3\alpha}{\lambda}+\frac{1}{\lambda}\right]\right\}$$

where Idl is the current moment of the source dipole pair (product of current and electrode separation), p_1 is the horizontal resistivity of the anisotropic earth, A is the anisotropy coefficient, r is the distance from the source dipole pair to the receiver dipole pair, and a is the angle at which the receiver dipole pair is located, as indicated in the inset in Figure 9. Equation 2 is valid only as long as the spacing distance r is only a small fraction of a skin depth in the earth. In equation 2, the first term is the static coupling between the electrodes, which contains the information about induced polarization, while the second term represents the inductive coupling, which is undesirable. The ratio of the two terms varies with the angle, a, as indicated by the curves in Figure 9. It is interesting to note that the least inductive coupling in proportion to static coupling is observed for dipoles that are in line with each other—the electrode system that is widely used at present in induced polarization surveys.

It appears that little can be done to minimize the problem of inductive coupling which has not already been done. The question, then, is how deep can induced polarization surveys be used? The answer is shown graphically in Figure 10, which gives the maximum spacing that may be used with an induced polarization survey, considering that a one percent residual current intensity is the maximum which can be tolerated from inductive coupling. For cover resistivities of a hundred ohmmeters and using frequencies of less than one cycle a second, spacings of 5000 feet may be used. However, for lower cover resistivities, electromagnetic coupling is a serious limitation. It is not likely that frequencies below a tenth of a cycle a second can be used because of the time involved in measurements and some doubt as to the behavior of the induced polarization effect at very low frequencies or very late times after excitation has been completed.

Although induced polarization surveys may possibly provide the penetration needed to see through a thick cover, the quality of the results suffers. In particular, with spacings of a mile or more, the exact location and quality of an ore body that contributes an anomaly are difficult to pinpoint. One cannot say easily whether an anomaly represents a larger low-grade source or a smaller high-grade source. Therefore, surface-based surveys are not likely to provide the definitive information on location and grade normally desired before drilling. Drill-hole-assisted surveys are a reasonable approach to the solution of this problem or the problem of an overburden that is too conductive to see through or too noisy to permit reliable interpretation of deep anomalies.

DRILL-HOLE-ASSISTED METHODS

Small-diameter drill holes, which may be drilled rather inexpensively, serve in geophysical exploration for deep-seated ore bodies. It is well known that the small core recovered from this kind of hole may be a misleading sample of the subsurface, and many such holes may be needed to evaluate an ore body reliably. Geophysics provides a means of increasing the sampling radius of a hole, though indirectly. One well-developed method is induction logging, described by Doll (1946), Duesterhoeft (1961), and Kaufman (1966). The in-hole tool consists of two coils, one that generates an electromagnetic field and the other that detects the secondary magnetic field from eddy currents in the rock. The system is shown in Figure 11. If the spacing between coils is less than a fifth of the skin depth at the frequency used, the secondary field samples the material for a distance around the hole roughly the same as the coil spacing. Considering the limitations imposed on coil size by a 2-inch-diameter hole, it is feasible to use coil separations approaching 100 meters. If conductive material is present within 100 meters of the drill hole, it would then contribute a measurable signal at the receiver. Figure 12 shows the response of this two-coil system plotted as a function of coil spacing, conductivity, and frequency.

Another approach to the use of underground electromagnetic sources is the observation of absorption of energy on transmission, rather than observation of reflected energy as in induction logging. Such a system is shown schematically in Figure 13. An electromagnetic field, generated by passing current between two electrode contacts in a well, propagates through the medium. Inasmuch as we are interested in adsorption of energy, it is desirable to choose a frequency that corresponds to one or two skin depths at the distances where measurements are to be made. At a frequency in the 1- to 10-kilocycle-a-second range, one might expect that measurements could be made at distances up to a mile, either underground in other boreholes or on the surface. Conductive zones would cast shadows in field strength, which could then be used to locate drill holes to best advantage in a second-stage drilling program.

SUMMARY

Large areas covered by thick rock layers may screen basement ore deposits from view. These would make an

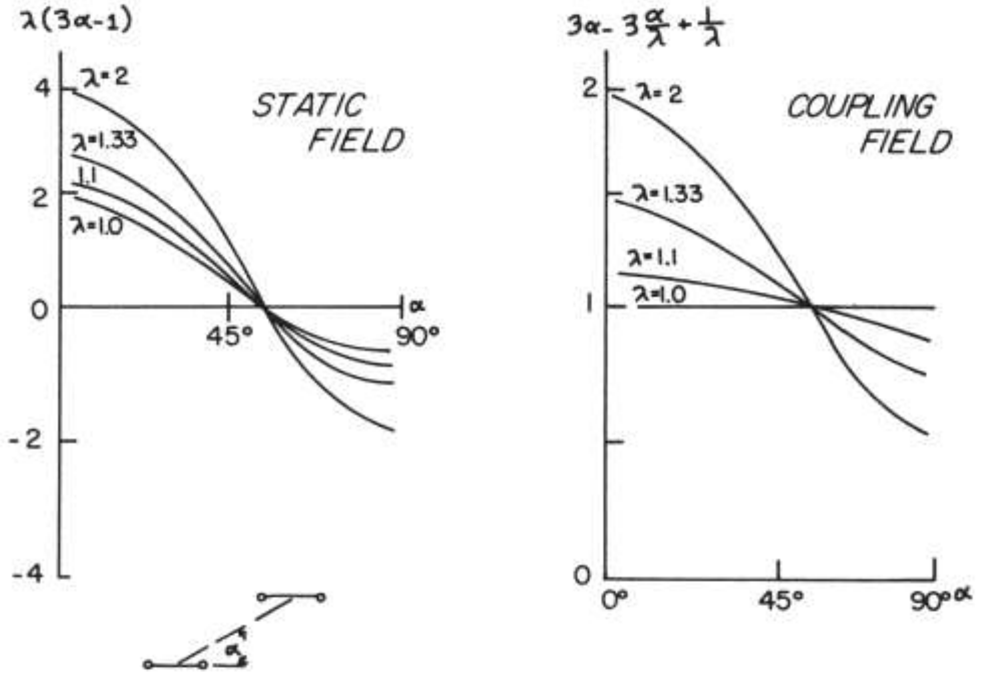

Figure 9

Theoretical Static-Field response and Induction Field response for GR 1 for a Dipole-Dipole induced polarization system

As a function of the angle at which the receiving dipole is offset from the suorce dipole. A uniform earth with an anisotropy λ between vertical and horizontal values of resistivity is assumed.

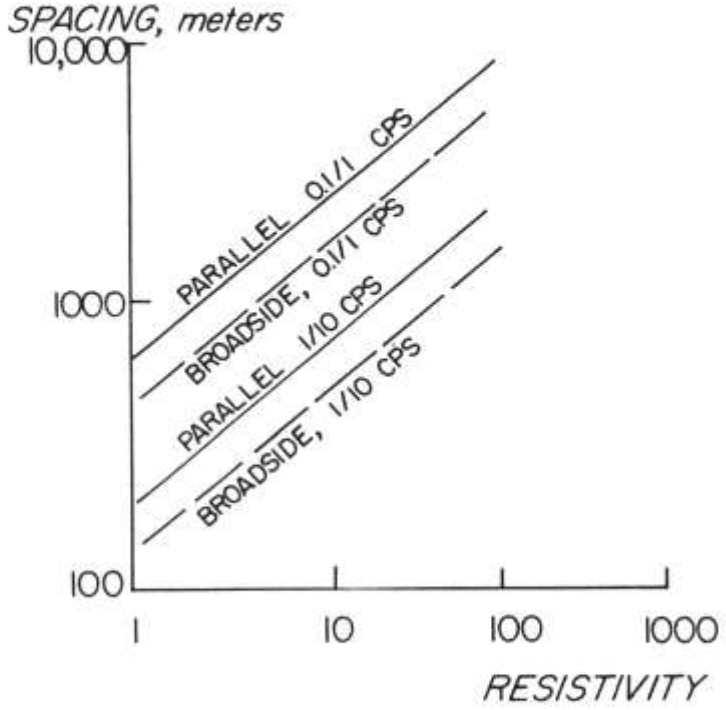

Figure 10

Maximum spacings used with the parallel inline or broadside-induced polarization arrays

If inductive coupling is to contrbiute no more than 1 percent normalized frequency effect. The earth is assumed to be uniform and isotropic.

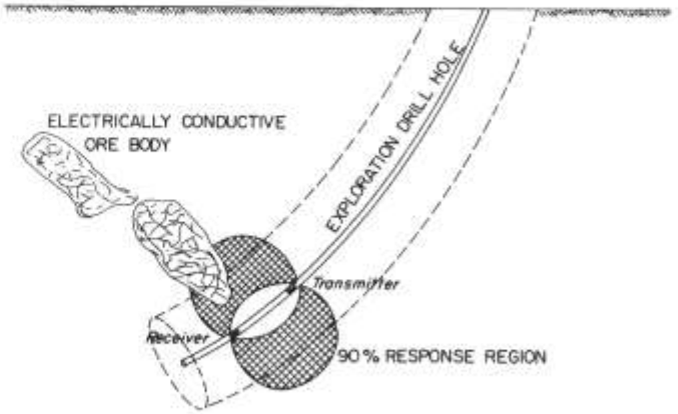

Figure 11
BASIC TWO-COIL ELECTROMAGNETIC LOGGING SYSTEM FOR EXTENDING THE RADIUS OF KNOWLEDGE ABOUT AN EXPLORATORY DRILL HOLE
The cross-hatched area indicates the volume of rock contributing 90 percent of the response if the frequency-conductivity product places operations in the so-called "Doll" region.

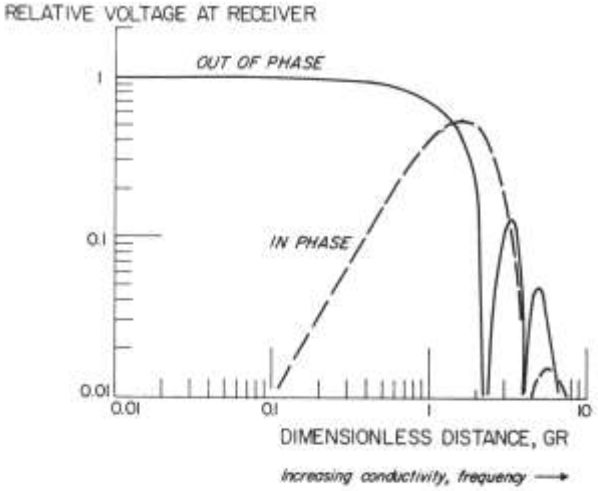

Figure 12
RESPONSE OF A TWO-COIL INDUCTION LOGGING SYSTEM IN A UNIFORM EARTH AS A FUNCTION OF COIL SPACING, CONDUCTIVITY, AND FREQUENCY

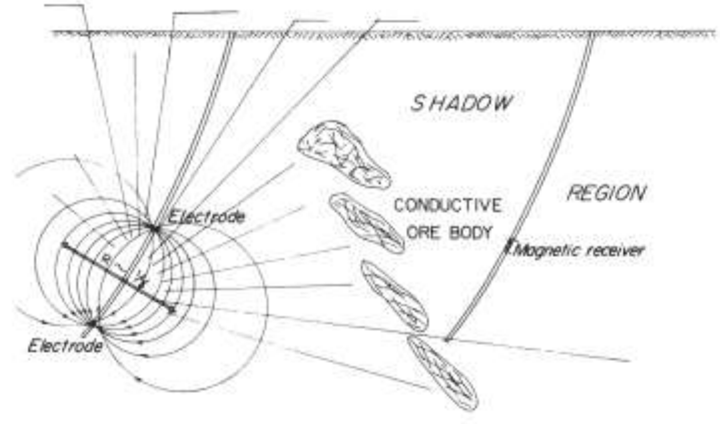

Figure 13
CONCEPT OF USING THE SCREENING OF INDUCTION FIELDS BY CONDUCTIVE ROCKS AS AN EXPLORATION METHOD

attractive exploration target if reliable geophysical exploration methods were available.

In recent years, the rather complicated theory on which electrical prospecting methods are based has been worked out in some detail. Consideration of this theory indicates that electrical methods can be used in exploration for deep-seated ore bodies. A logical program would consist of high-altitude electromagnetic surveys to locate favorable subcover areas, followed by deep-penetration surface-based induced polarization surveys if the nature of the cover permits. However, detailed exploration should be based on drill-hole-assisted surveys. Likely areas should be drilled with a wide-spaced drilling program, perhaps on a half-mile or one-mile grid. The sampling radius of the reconnaissance drilling would be extended to about 300 feet by borehole electromagnetic surveys, then the area between boreholes would be investigated by electromagnetic transmission surveys. Subsequent drilling would be based on the location of conductors seen with the drill-hole-assisted surveys.

For such a program to be economically successful, considerable care would need to be taken to assure that the geophysical exploration techniques were mated to the exploration problem, as formulated by the physical properties of the host rock and the anticipated ore bodies. To repeat, the essential ingredient that makes this feasible today, where it was not ten years ago, is the availability of reasonably complete theoretical backgrounds for the geophysical methods.

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Engineering Problems and Downhole Geophysical Solutions

by H. W. Lawrence and R. W. Baltosser
Birdwell Division, Seismograph Service
Corp., Tulsa, Oklahoma

Drilling holes in the ground is a fundamental process in two of the world's primary industries, mining and petroleum. These have similar basic aims in their drilling programs in that both drill to explore for the end purpose of exploiting a natural resource. Beyond these basic aims, however, their methods and techniques necessarily diverge rapidly, both in the actual drilling operation and in the means of extracting required information from the drilled hole.

The petroleum geologist with exploration responsibilities will rarely drill to less than 5000 feet. The holes he drills vary in diameter upward from 5 inches. Cores will rarely be cut. If the hole encounters commercial accumulations of oil and gas, the same hole is used to exploit the deposit. The mining geologist, on the other hand, will almost never drill to 5000 feet, his holes vary downward in diameter from 5 inches, he will probably attempt to recover core from top to bottom, and, if the hole encounters commercial-grade ore, he must drill more holes to outline the deposit.

The oil man relies for information concerning the formations penetrated by the hole on measurements of various physical parameters that lend themselves to measurement by devices lowered into the hole. The mining man depends almost entirely on the core he has cut for the information he needs concerning the rocks penetrated. Obviously, these two approaches to information-gathering developed because they offered specific advantages to the industry requiring the information. Oil industry research, therefore, became rather naturally directed toward downhole measurements, while the mining industry concentrated on the development of more efficient methods of cutting core. Both industries have undeniably improved their techniques. However, we would like to suggest that it is time that more of their respective technologies are shared.

Since our particular field is downhole geophysical measurements, we feel qualified to suggest those oil-field techniques that might prove applicable to the mining industry. And since our time is limited, we intend to concentrate on only one of those which we believe might have something to offer.

One of the standard measurements made on a core sample is the velocity with which it will transmit sonic signals. Velocity values are meaningful with regard to the strength of the rock, its rippability, and blastability. Velocity observations made on core samples are good, but they can be bettered, for several reasons, by in-situ observations. The technique known as Continuous Velocity Logging makes possible such in-situ observations. This technique of measuring and continuously recording compressional wave travel times in a borehole is now 15 or 20 years old and is no doubt familiar to most of you. Figure 1 shows the downhole tool. It consists, basically, of a transmitter and a receiver separated by an acoustic isolator. The transmitter is a magnetostrictive device pulsed at about 15 times a second. The receiver is a crystal device.

The C VL system depends on refraction and mode conversion to get the sonic signal from the transmitter to the receiver. Figure 2 may help to illustrate the process. The signal leaves the transmitter as a compressional wave and travels through the drilling fluid to the face of the borehole, where a number of things happen. Part of the energy is transmitted directly outward into the formation and is lost. Another part arriving at the borehole face at the critical angle as defined by Snell's Law is refracted and travels through the formation parallel to the borehole, still as a compressional wave. Another part of the signal arriving at the borehole face at a different angle goes through the phenomenon known as mode conversion, becomes shear energy, and travels parallel to the borehole as a shear wave. Still another part of the energy generates what is variously known as boundary, tube, or Stoneley waves, which are dilatational waves analogous to surface Rayleigh waves.

Fortunately, all these forms of energy travel through the formation at different velocities. The compressional wave is the fastest, followed next by the shear wave, and finally by the boundary wave. Refraction and mode conversion, both continuous processes, permit the signal arrivals to be impressed on the receiver when they arrive opposite the receiver. Their sequence and order of arrival can be pictured on an oscilloscope and appear as in Figure 3. Zero time, or time of signal generation, is shown, followed by compressional, shear, and boundary modes.

If the scope of Figure 3 were to be photographed at discrete depth intervals as a tool is pulled upward in the hole, logs such as that illustrated in Figure 4 would be produce d. This illustration demonstrates the features previously mentioned, that is, compressional, shear, and boundary wave arrivals, but in a form extremely difficult to work with.

It is possible, however, to display the signal on an oscilloscope in another mode. Figure 5A again illustrates the standard amplitude-modulated display just discussed. Figure 5B is an intensity-modulated or variable density form of display comparable to a single line of a TV picture. When

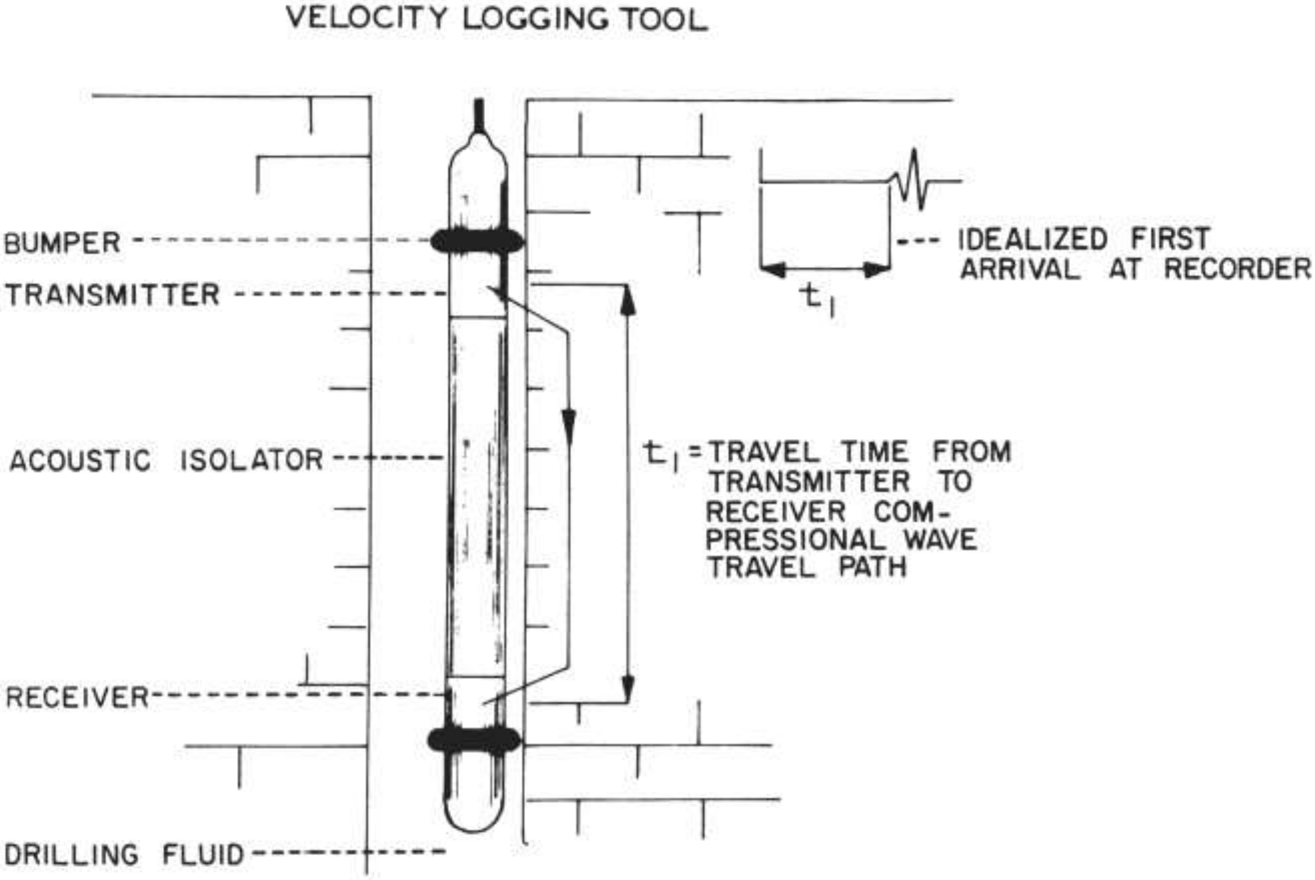

Figure 1
DOWNHOLE VELOCITY LOGGING TOOL

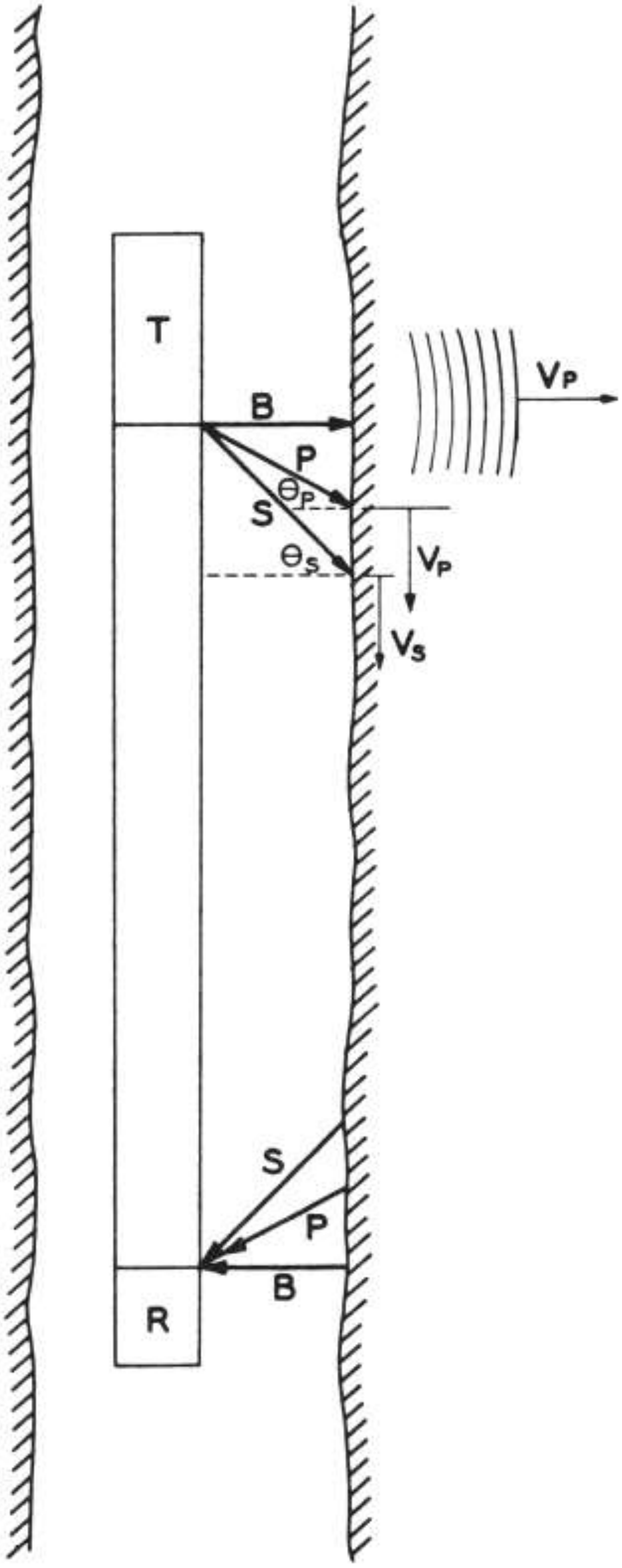

Figure 2
SONIC SIGNAL PATHS AT THE BOREHOLE FACE

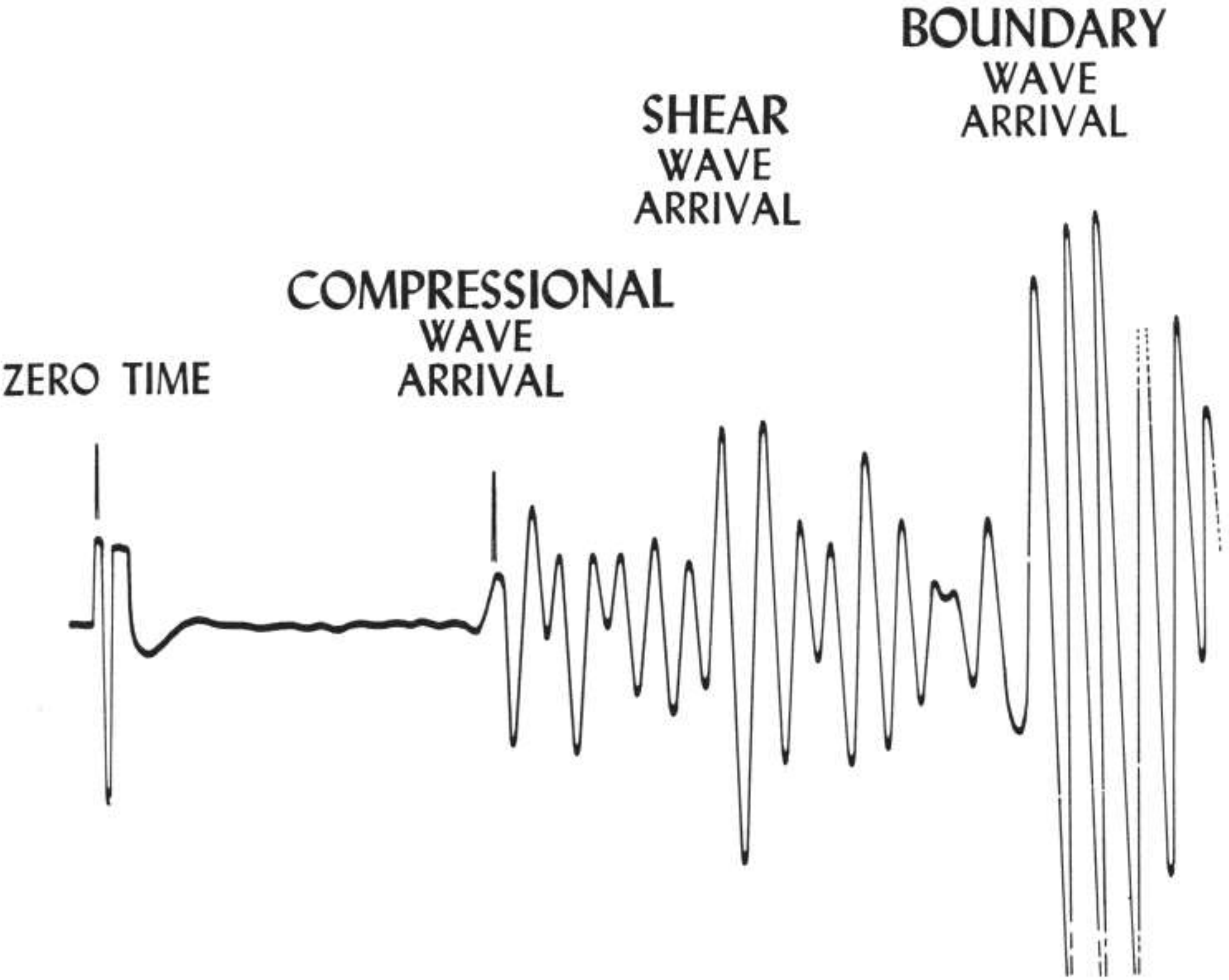

Figure 3
Sequence and Order of Arrival of Energy Waves

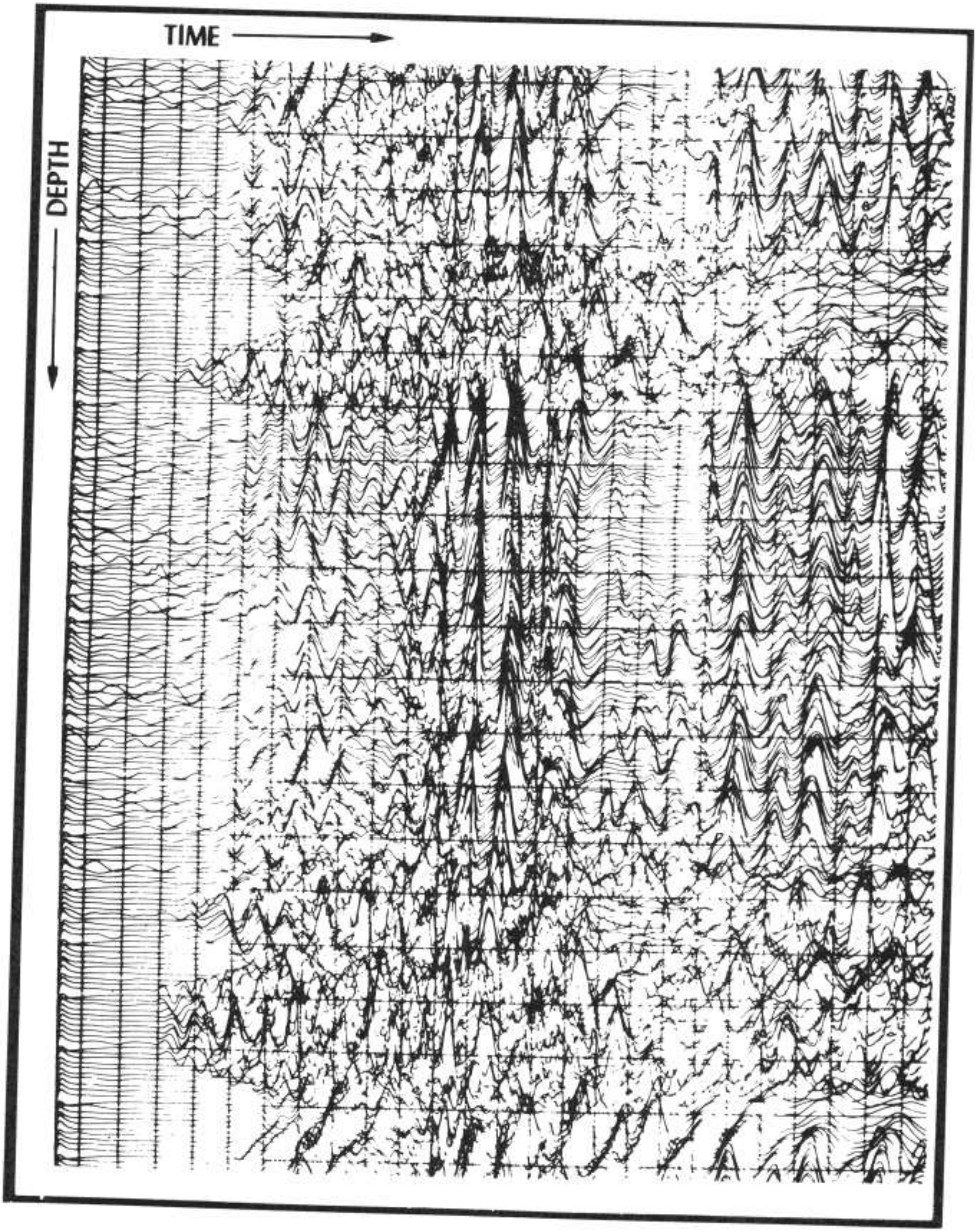

Figure 4
Logs illustrating wave arrivals

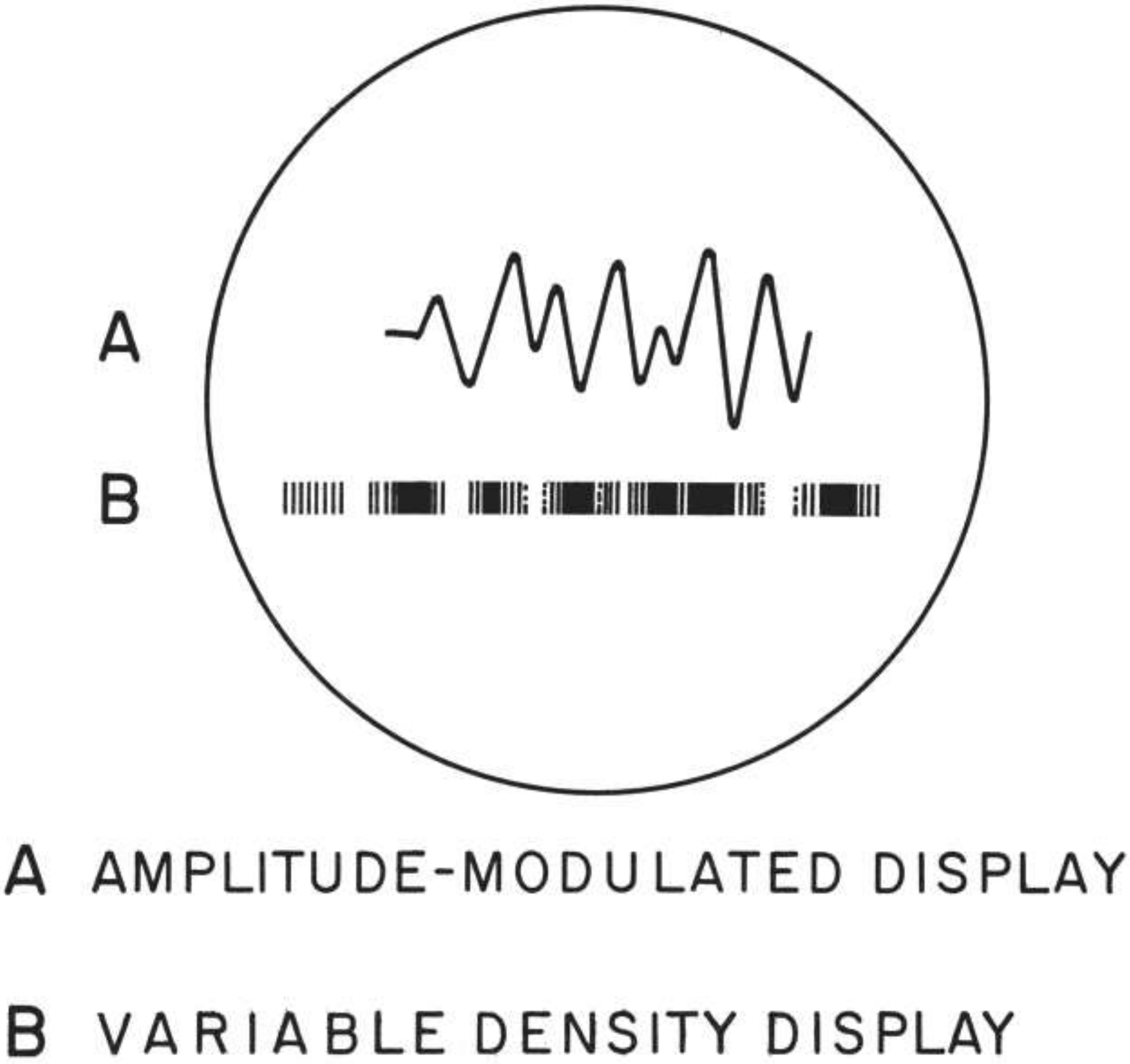

Figure 5
Oscilloscope signals

compared with the amplitude-modulated display, it shows light for peaks and dark for troughs. Now, if a film were moved acorss the face of a scope with the signal in the intensity-modulated mode, a log such as that shown in Figure 6 would be produced. Time increases from left to right, depth from top to bottom, with the heavy horizontal lines being at 10-foot intervals. In this illustration, the first arrivals of the compressional, shear, and boundary events are easily discernible. This type of display is known as a 3-D Velocity Log.

The 3-D Log offers considerable information using only "eyeball" examination. Figure 7 illustrates a core log with the corresponding section of 3-D Velocity Log. Variations in velocity are obvious with lithologic changes; variations in signal strength are apparent in the fractured sections, particularly at the shear wave arrival; the highly fractured, broken zone and silty sections indicated on the core log can be easily identified on the 3-D Log; the two lower siltstone sections, one indicated as having many healed fractures and the other apparently unfractured, are very different in appearance.

There is also considerable diagnostic value, in some instances, in an eyeball examination of the 3-D Log. The next few log examples are all from holes drilled in concrete caissons. These particular caissons are approximately 120 feet in depth, 10 to 12 feet in diameter, and poured in what is called the "Chicago Method." This method might be described as a below-surface slip-forming technique in which the forms are pulled upward as the concrete is poured. On this project, one of the completed caissons was observed to have moved, so an examination of the caissons was undertaken.

Figure 8 shows a section of a log from one caisson that has an obvious defect. Both compressional and shear wave velocities drop off very markedly. This log was made using a spacing of 6 feet between the transmitter and the receiver. Figure 9, on the left, shows the corresponding section from a log made of the same caisson using 3-foot spacing and indicating the same defect. The right half of Figure 9 is what we call a hole-to-hole log. There were two holes drilled in this caisson. A transmitter was lowered in one hole and a receiver in the other. The two were pulled up simultaneously and a "picture" of the concrete between the two holes was obtained. The same defect is again shown. Subsequent repair operations revealed a clay inclusion in the concrete.

Figure 10 again shows three logs from one caisson. The log on the left, spaced at 6 feet, seems to indicate a 6-foot anomalous section in the caisson. The center log, with 3-foot spacing, indicates the anomaly to be of only 3-foot vertical extent. On the right, the hole-to-hole log shows the defect to be of only very limited vertical extent. On being mined out, this caisson was found to have a fracture of approximately three-quarters inch of vertical separation.

The 3-D Velocity Log has further and more significant uses in the field of rock mechanics. Relations between compressional and shear wave velocities and density have appeared in the literature for a number of years. Figure 11 shows the mathematics involved in extracting Poisson's Ratio, Young's Modulus, shear modulus, and bulk modulus. The 3-D Log records the compressional and shear wave velocities; the third factor, density, is available from gamma-gamma density logs or from actual measurement of samples. With the above types of data and a suitable computer program, it is possible to produce a foot-by-foot analysis showing the values indicated in Figure 12; that is, depth, compressional and shear wave velocities, density, Poisson's Ratio, the elastic moduli, and a couple of "bonus" features, porosity and water saturation. The last two are empirically derived values and are probably more qualitative than quantitative.

The calculated elastic moduli values are, of course, dynamic values. We recognize, even though we may not completely understand, the controversy over where and when dynamic as opposed to static values are applicable. A reasonably comprehensive review of the available literature served mainly to confirm that a controversy certainly does exist. We were, however, able to draw the following fairly clear inferences from the review:

(1) There are numerous apparent discrepancies between the statements of the definitions of parameters and the actual measurements. This is particularly true with respect to Poisson's Ratio.

(2) There is a definite discrepancy between static measurements of stress and dynamic measurements of stress. This divergence appears to be related to the degree of stress relief, the dynamic in-situ measurements being made on partially stress-relieved samples, and the static measurements on wholly stress relieved samples. The degree of stress relief is, we believe, related to time. This suggests that a time equation is required to correlate the two measurements.

(3) All published data on elastic moduli values are based on empirical observation and should represent the mean, lower limit in respect to allowable stress.

(4) Rock mechanics will of necessity have to accumulate sufficient data on both static and dynamic measurements to arrive at a mean acceptable value for (a) general rock types and (b) recommendations for obtaining specific values for local conditions.

For whatever it may be worth, personal observations as well as published material indicate that dynamically determined values for the elastic moduli of rocks are consistently higher than statically determined values.

The controversy aside, our premise here is that in-situ dynamic measurements should have some applicability to

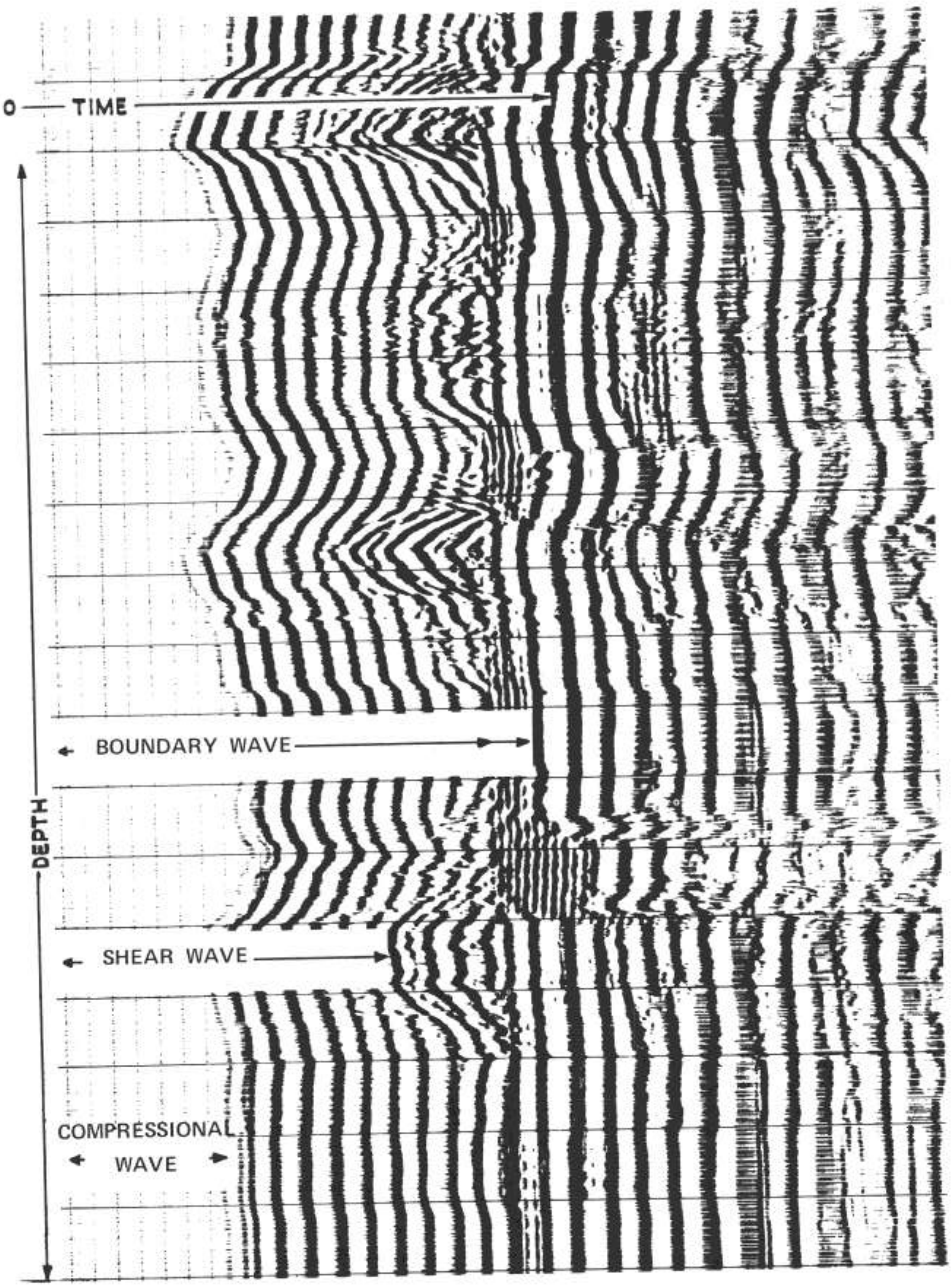

Figure 6
3-D VELOCITY LOG

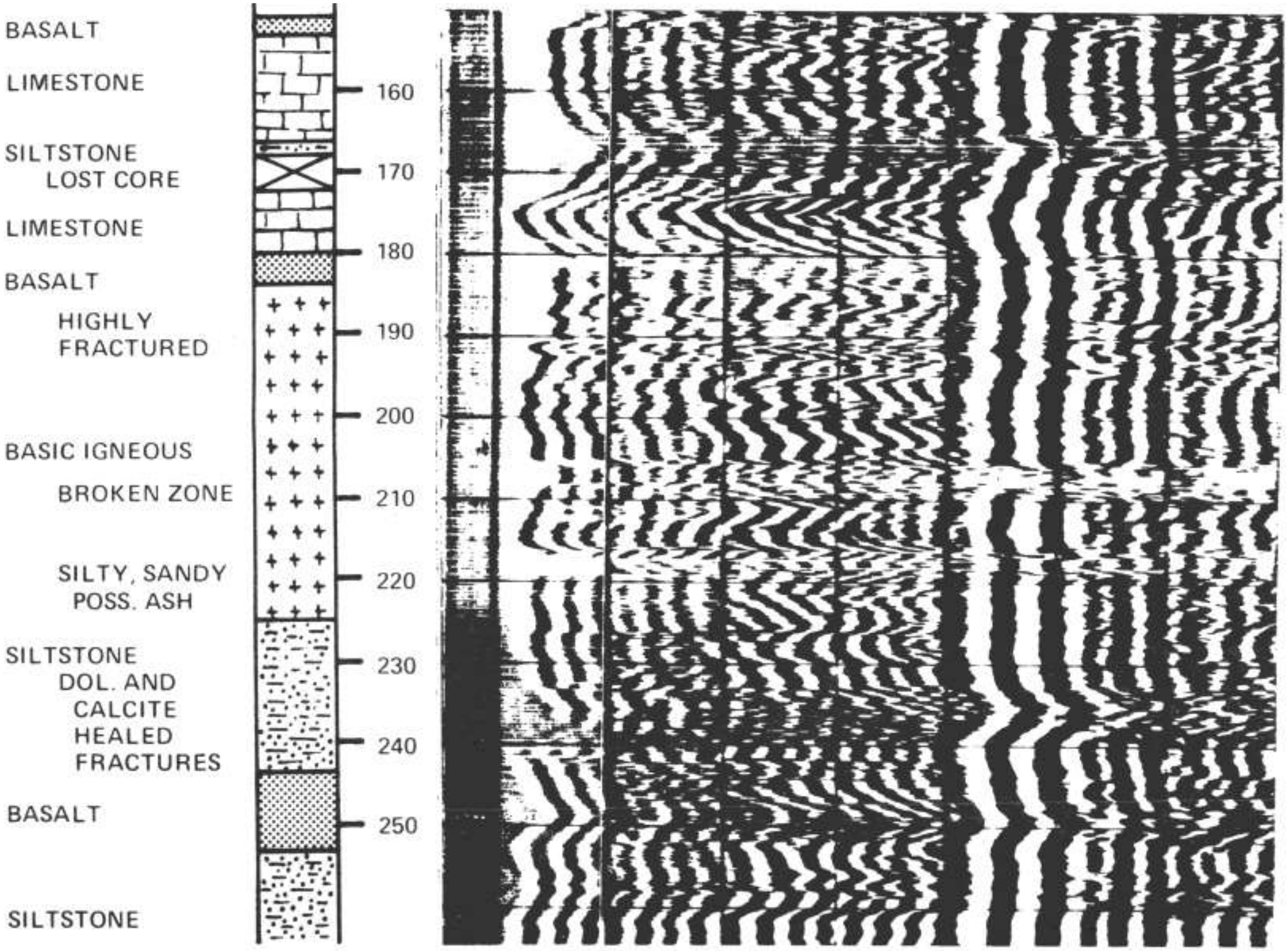

Figure 7
Comparison of core log with 3-D velocity log

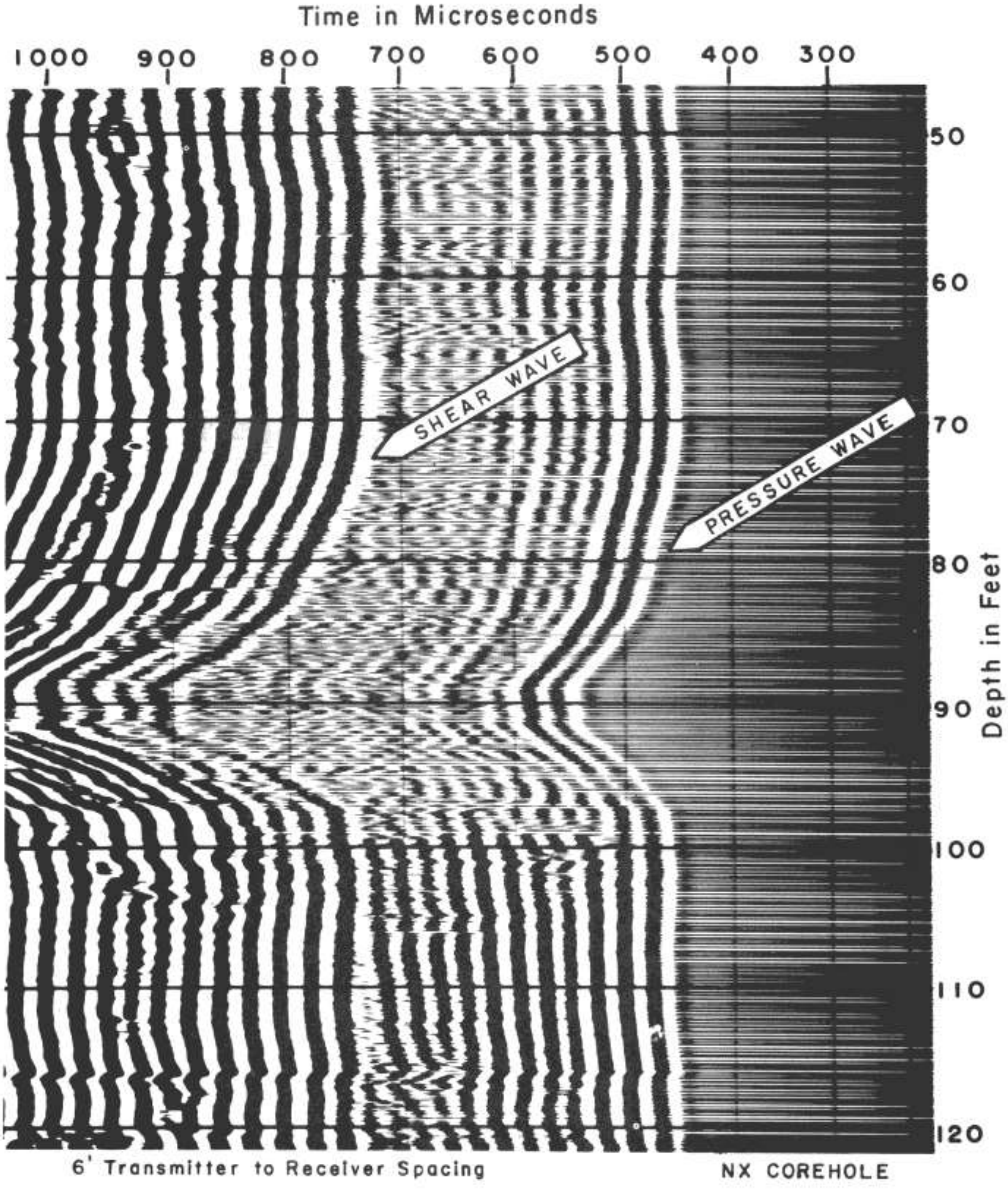

Figure 8
Log of a caisson showing a defect using 6-foot spacing

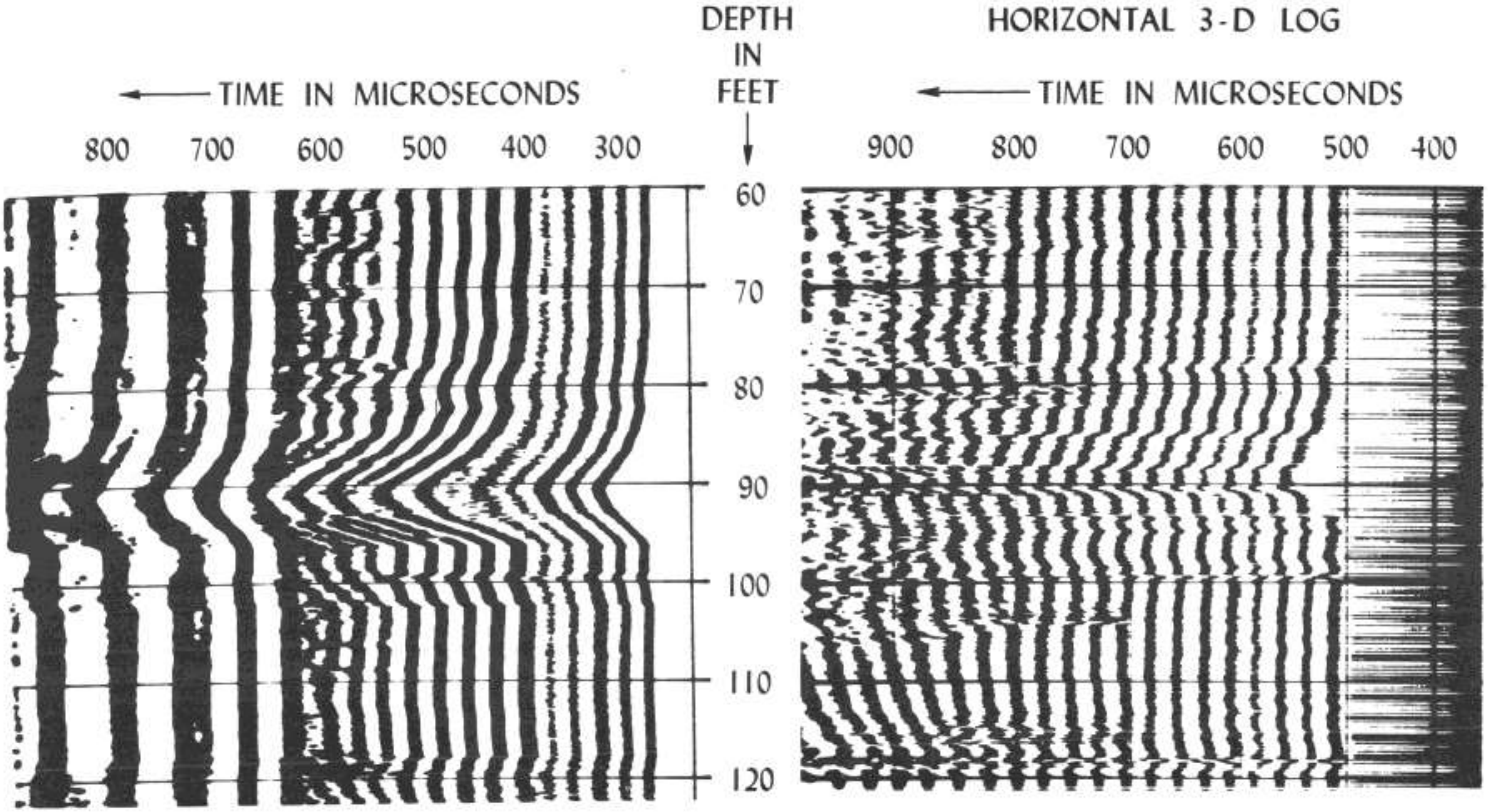

Figure 9
Logs of a caisson showing a defect using 3-foot spacing

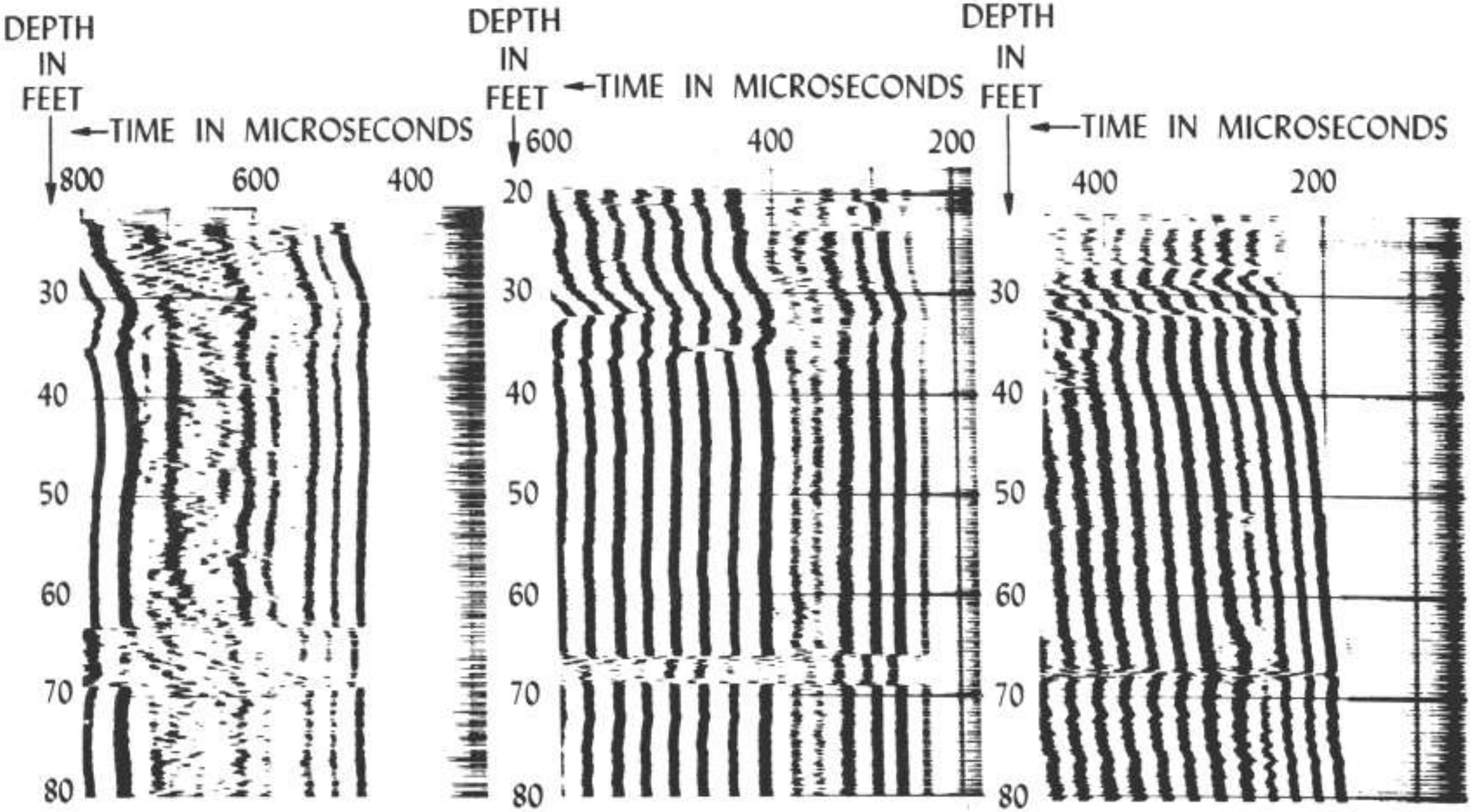

Figure 10
Comparison of logs from 6-foot and 3-foot spacing with a hole-to-hole log
(on right.)

$$\sigma = \frac{\frac{1}{2}\left(\frac{Vp}{Vs}\right)^2 - 1}{\left(\frac{Vp}{Vs}\right)^2 - 1}$$

Where: σ = Poisson's Ratio
Vp = Compressional Wave Velocity
Vs = Shear Wave Velocity

Shear Modulus: $\mu = \rho V_s{}^2$

Young's Modulus: $E = 2\mu\,(1+\sigma)$

Bulk Modulus: $B = \rho V_p^2 - \frac{4}{3}\mu$

WHERE ρ = Density

σ = Poisson's Ratio

Vs = Shear Wave Velocity

Vp = Pressure Wave Velocity

Figure 11
CALCULATION OF POISSION'S RATIO

TABULATION OF DATA DERIVED FROM 3D LOG
OF CONCRETE TEST BORING DEPTH IN FT. VP & VS IN
FT/SEC.POR IN %.DEN IN LBS/CUF T. TIME IN MICSEC.

			MODULI IN 10 TO 4TH POUNDS/SQ IN							
DEPTH	VP	VS	SHEAR	BULK	YOUNGS	POROS.	DENSITY	POISSON	TAUP	TAUS
60.	14220.	8599.	247.	346.	599.	18.	154.8	0.212	438.	712.
62.	14176.	8614.	253.	348.	611.	18.	157.9	0.207	439.	710.
64.	14220.	8630.	259.	358.	626.	17.	161.1	0.208	438.	709.
66.	14491.	8661.	262.	384.	640.	16.	161.7	0.222	430.	707.
68.	14491.	8630.	261.	388.	639.	16.	162.3	0.225	430.	709.
70.	14399.	8584.	253.	375.	620.	17.	159.2	0.224	433.	713.
72.	14309.	8554.	246.	361.	602.	17.	156.1	0.222	435.	715.
74.	14220.	8494.	239.	351.	585.	18.	153.6	0.223	438.	720.
76.	13875.	8376.	228.	321.	553.	19.	150.5	0.213	448.	730.
78.	13667.	8192.	215.	312.	525.	20.	148.6	0.220	455.	746.
80.	13545.	8082.	206.	304.	504.	20.	146.1	0.224	459.	756.
82.	13386.	7936.	194.	294.	478.	21.	143.0	0.229	464.	769.
84.	12968.	7758.	183.	268.	448.	23.	141.1	0.221	478.	787.
86.	12506.	7424.	164.	247.	403.	24.	138.0	0.228	495.	821.
88.	11826	7045.	145.	215.	356.	27.	135.5	0.225	523.	864.
90.	11765.	6934.	139.	215.	344.	27.	134.2	0.234	525.	877.
92.	11856.	6954.	147.	231.	363.	26.	140.5	0.238	521.	875.
94.	12786.	7447.	176.	285.	439.	21.	147.3	0.243	485.	818.
96.	13465.	8015.	215.	320.	526.	19.	154.8	0.226	461.	762.
98.	13959.	8420.	242.	342.	587.	18.	157.9	0.214	446.	726.
100.	14089.	8449.	244.	354.	596.	18.	158.6	0.219	442.	724.
102.	14089.	8554.	251.	347.	607.	18.	159.2	0.208	442.	715.
104.	14089.	8524.	253.	353.	612.	18.	161.1	0.211	442.	718.
106.	14132.	8509.	252.	359.	612.	17.	161.1	0.216	440.	719.
108.	13959.	8479.	247.	340.	597.	18.	159.2	0.208	446.	721.
110.	14002.	8479.	247.	344.	598.	18.	159.2	0.211	444.	721.

Figure 12
TABULATION OF DATA FROM 3-D LOG

mining engineering problems. Let us consider Poisson's Ratio, which involves only the pressure and shear wave velocities, the mathematical expression of which was shown earlier. The commonly accepted definition for Poisson's Ratio (from Eshback, *Handbook of Engineering Fundamentals*, Wiley Handbook Series) is: "The elongation or shortening of a bar under axial stress is accompanied by a reduction of the cross-sectional area under tension and an increase in the cross-sectional area under compression. It has been established by experiment that the lateral unit deformation or change per unit diameter or other lateral dimension is proportional to the linear unit elongation or shortening." This expresses a necessary engineering concept for a stressed body within the elastic limits but does not express any of the stress characteristics of a loaded body. Recent experimental data suggest that there is a definite change of Poisson's Ratio with pressure change. In this instance, if we consider a pillar in a mine, we can find in the literature several studies that define the loading through the pillar. An examination of these studies shows that the stress load in the pillar varies from tension at the unconfined edges to compression at the center. This would suggest that dynamic measurement of Poisson's Ratio might vary from positive values in the center or compressed zone to negative values in those zones under tension. It seems reasonable, by extension, to assume that a similar condition would exist at a slope face. Perhaps we could detect a slope in a condition of instability with a log of Poisson's Ratio.

Interestingly, preliminary work on the Iron Range indicates that both Poisson's Ratio and the shear modulus correlate with the index of grindability for taconite.

Another consideration involving shear and Young's moduli has been discussed by K. P. Desai in his doctoral dissertation (Tulsa University, 1968). He established that the shear modulus increases with pressure. This can be considered almost axiomatic since the density, except from slight compaction, will remain the same while the shear wave travel time will decrease with pressure. Since Poisson's Ratio is a dimensionless number, then Young's Modulus must change. Can the higher value for Young's Modulus represent some measure of the actual in-situ loading? We need considerably more field data to answer many of these questions.

The 3-D Velocity Log is currently being used on the AEC Test Sites in Nevada and Amchitka in containment studies. It was used by the Corps of Engineers in a study of a sea-level canal route in Panama. It has been used at various building sites around the country and on the Chicagoland Deep Tunnel Project. Various dam sites here and abroad have used data from the log. Preliminary work has been done on the Mesabi Range in a study on comminution of the taconite ores. We believe it will become an increasingly important tool in engineering geophysics, with applications in both mining and construction.

There are a number of other downhole devices that may have some application in the mining industry. Kennecott, for example, has found uses for certain downhole tools in an investigation of leaching. Other devices include gamma-gamma density, magnetic susceptibility, induced polarization, nuclear activation and spectral analysis, and the resistivity logs, including SP.

We realize that there is an extremely wide area in which our knowledge is deficient. We need to know more about your problems and welcome discussion of them.

Geothermal Power Resources in the Southwest

by Henry S. Birdseye

Geothermal steam is gaining increasing recognition as a source of low-cost electrical energy and mineral extraction in many parts of the world. Those districts exhibiting such abnormal temperatures as to approach or exceed the boiling point of water are broadly classed as hyperthermal. High-intensity thermal anomalies of commercial value are invariably believed to be in proximity to magmatic heat sources, while low-intensity anomalies may result from the friction of tectonic movement, exothermic chemical reactions, radioactivity, and the like.

Prior to the drilling of exploratory test wells, the evaluation of hyperthermal prospects is threefold: (1) geologic mapping and reconnaissance, (2) geochemical surveying, and (3) geophysical surveying. The geologic phase consists of determining the over-all environment, with particular reference to volcano-tectonic history, fault patterns, and configuration of affiliated mineral deposits. Geochemical studies provide useful data for predicting reservoir temperature, heat flow, the possibility of dry steam vs. wet steam, and the likelihood of corrosion and deposition. Geophysical surveying consists of shallow-depth measurement of geothermal gradients, supplemented by gravity, magnetic, electrical resistivity, and infrared surveys.

Future geothermal exploration may include deep drilling in an effort to intercept nascent ore solutions, nuclear detonations to create convection channels in low-permeability hot water systems, and the use of hyperaltitude photographic and heat-sensoring techniques from orbiting satellites.

Although geothermal energy is one of the newest natural resources to be utilized by man, it is also one of the oldest. Prehistoric man undoubtedly frequented hot spring areas for water and space heating and perhaps even for cooking and bathing. In his *Iliad*, written circa 850 B.C., Homer referred to hot springs near ancient Troy. Thermal springs are noted in the Old Testament of the Bible (Waring, 1965). The first written mention of the fumaroles at Lardarello, Italy, was by the Roman, Lucretius Carus, in the first century B.C. (Brooks, 1966).

Late in the eighteenth century, the first economic use found for thermal springs was in Iceland, where hot water was used to recover salt from sea water by evaporation. At about the same time, borax was first separated commer cially at Lardarello, Italy, followed a few decades later by the production of boric acid (Kiersch, 1964).

In 1904, geothermal steam was first used to generate electricity in a small dynamo at Lardarello, with sufficient output to light five incandescent bulbs. Eight years later, Prince Conti installed a 250-kilowatt steam turbogenerator at Lardarello, pioneering in the truly commercial application of this unique resource (Brooks). The Italian facilities, which were destroyed during World War II, were later rebuilt and expanded with U.S. aid. New Zealand's large generating plants at Wairakei commenced operation in 1958, followed in 1960 by the first geothermal power plant in the United States, at The Geysers, Sonoma County, California, which also is the only plant constructed by private enterprise.

At this writing, Italy's geothermal power plants now generate almost 400 megawatts of electricity, which would be adequate to run the entire national railway system. Nearly an equal amount is generated on New Zealand's North Island. The three units at The Geysers in northern California, operated by Pacific Gas and Electric Company, generate 55 megawatts, with a continuous expansion programmed through 1975 to a maximum in excess of 335 megawatts. I Mexico, some 25 megawatts are being generated geothermally, while Iceland reports 15 megawatts, Russia is credited with about 5 megawatts, and Japan and Katanga each have small units of less than 1 megawatt.

Although hyperthermal areas are by no means ubiquitous, they are widely distributed throughout the world and are too numerous to describe individually in this paper. For example, geothermal localities occur in at least 24 states of the United States, 5 countries of Central America, 8 countries of South America, 19 in Europe, 27 in Africa, 23 countries of Asia, and 20 island groups in the Pacific Ocean. Within the context of this paper, there will be some discussion of the gross geological factors that exert a dominant influence in the global distribution of geothermal trends, supplemented by more detailed descriptions of specific localities—geothermal geometry, if you please.

CHARACTERISTICS OF HYPERTHERMAL AREAS

The normal, or average, geothermal gradient in the earth's crust is on the order of 1°C per 27 to 60 meters. Thus, a depth of some 3000 meters is usually required to reach 100° C. From an area of normal gradient and thermal conductivity, the heat flow, which is the product of thermal gradient times thermal conductivity, is about 12,000 cal. per second per square kilometer (Birch, 1954). In hyperthermal areas, heat flow may be at least 120 times this amount (White, 1961).

Deep exploratory wells in areas of normal gradient have recorded temperatures as high as 234°C (454°F) at a depth of about 6300 meters (20,600 feet). Despite the great cost o f drilling to such depths in nonanomalous areas, the Russians are investigating the feasibility of recycling meteoric waters in ultradeep wells for space heating and power generation (Pokrovsky, 1964).

By definition, hyperthermal occurrences are those of abnormal heat flow, although some authors restrict the term *hyperthermal* to anomalies with surface temperatures exceeding the boiling point of water. In the present paper, *hyperthermal* describes all thermal anomalies of sufficiently high temperature as to encourage commercial exploitation. Hyperthermal areas are generally classed as low-intensity or high-intensity, according to heat flow and temperature (White, 1961).

Low-intensity or low-temperature thermal anomalies are of little commercial significance because their dimensions and heat flow presage insufficient total energy and brief longevity. These relatively common but minor anomalies can be caused by disintegration of radioactive substances, exothermic chemical reactions such as the oxidation of pyrite, expiring vulcanism, and the friction of fault movement. Space heating may prove to be the only commercial application of low-intensity thermal waters.

High-intensity thermal areas, which have been estimated to number less than 100 in the United States, are defined as having heat flows at least fifty times normal (White, 1961). Most geothermal experts believe that the quantity of heat flow in a high-intensity area demands the proximity of geologically young intrusive or extrusive igneous rocks. In the vast majority of such areas, Tertiary or Quaternary volcanic rocks can be observed in the immediate vicinity of the hyperthemal surface indications, providing a conspicuous source for the needed heat. However, several notable occurrences, such as at Lardarello, Italy, Long Valley and the Salton Sea, California, and Cerro Prieto, Mexico, exhibit a complete absence of volcanic outcrops within radii of up to more than a score of kilometers. Even in these instances, concealed magmatic intrusions, not yet penetrated by drilling, are the most logical origin for the strong geothermal occurrences. The absence of volcanic outcrops is sometimes found in combination with the sub flow of large quantities of cold ground water, for example, in the foothills of the Colorado Rockies, so that a high actual heat flow can thus be deceptively quenched.

Conduits for the circulation of meteoric and, to a much lesser extent, juvenile waters are considered essential in the convection systems of major hyperthermal anomalies. Faults and fractures invariably provide the principal vertical and lateral permeabilities, supplementing the primary permeability of the rock strata. Not enough heat can be conducted directly through the rock mass from the deep-seated magmatic source to develop high-temperature conditions in the absence of permeability (Kiersch).

Surface leakage, in the form of hot springs, steam vents, fumaroles, or geysers, frequently characterizes the presence of high-intensity anomalies. Although these surface signs are a useful exploration tool, they nevertheless constitute leaks in the system and thus may cause lower pressure and temperature than in a closed trap.

PROSPECTING AND EVALUATION TECHNIQUES

Commercially significant geothermal anomalies require the fulfillment of four basic geologic needs: a heat source, large quantitites of meteoric water in a convection system, the proper combination of structural conditions, and appropriate lithology for a closed reservoir or trap. A threefold approach to the evaluation of these factors is recommended:

Geologic Mapping and Reconnaissance. The purpose of this initial phase of prospecting is to determine the over-all environment of a hyperthermal area.

Of primary importance is the delineation of the geothermal geometry, as shown by structural expression. Without exception, steeply dipping normal or strike-slip faults provide conduits for the circulation of meteoric water in an extensive convection system in which heat is transferred by conduction from the hot volcanic source rock. Fault and fissure patterns vary widely according to the locality. Some typical examples include the inter-montane graben valley at Salton Sea, the elliptical Long Valley, California volcano-tectonic subsidence structure, the circular Jemez Caldera of New Mexico, and the right-lateral subparallel faults of The Geysers district, California. Photogeology is an indispensable adjunct to surface mapping of structural details.

Equally important is the establishemnt of areal volcano-tectonic history and thus the age relationships of geologic events and features. From these can be deduced the approximate evolution of the geothermal system and, hopefully, an opinion as to its ultimate heat flow.

A regional study of the lithology and physical properties of rock units permits projection of these data into the subsurface of the prospect locality. A principal reason for this phase is the importance of permeability and effective porosity as they affect the migration and entrapment of fluids in the system.

Mapping of mineral deposits, where present, is a useful guide to the configuration of fluid conduits, heat flow, and the chemistry of fluids deep within the hyperthermal system. In addition, the hyperthermally associated minerals themselves may be of substantial economic value, for example, the extensive cinnabar deposits at Sulphur Bank, California, and the fluorite deposits at Poncha Hot Springs, Colorado. Great significance is attached to the remarkable metalliferous brine produced with steam just to the south of the Salton Sea. It is quite possible that the value of such components as sodium, calcium, and potassium chlorides, together with copper and silver, will far exceed the energy value of geothermal steam at this locality, and large commitments for brine extraction and separation have already been made. Other examples of minerals associated with hyperthermal occurrences include the following: gold, silver, stibnite, and cinnabar at Steamboat Springs, Nevada; gold and silver at Wairakei, New Zealand; orpiment and realgar at Norris Basin (Yellowstone), Montana; manganese and tungsten at Crater Hot Springs, Utah, and Luis Lopez, New Mexico; and sulfur at Sulphur Springs, New Mexico. White (1955) reports similarities of certain of these high-temperature spring systems to epithermal gold-silver deposits.

Although it now appears unlikely that the Salton Sea brine is of magmatic origin (Craig, 1966), many authorities believe that deep drilling of certain hyperthermal areas will reveal truly magmatic ore solutions, most of whose components have not yet been reached by the drill or which precipitate and fail to reach the surface in present wells.

The meticulous geologist will uncover other useful tools in field mapping and reconnaissance. For example, a hyperthermal anomaly south of Lordsburg, New Mexico, is sharply outlined by vegetational changes, although surface temperatures exceed normal by only a few degrees centigrade.

Geochemical Surveying. The composition of thermal waters can be a useful tool in predicting characteristics of hyperthermal areas. These waters may be either juvenile (magmatic) or meteoric in origin, though most experts agree, on the basis of isotope studies, that meteoric waters predominate to 90 to 100 percent of the total. Nevertheless, it has been estimated (Clark, 1924) that a cubic kilometer of granite would yield 26,400,000 metric tons of water. White (1961) believes that magmatically generated waters contain less than 20 ppm of chloride and that this is a guide to dry-steam areas. Conversely, White (1961) and Burgassi (1962) believe that chloride content of more than 20 ppm indicates meteoric water. High chloride content is a sign that dry steam is unlikely (Kiersch) and is, in fact, a common indicator of hot-water areas. Besides low chloride content, spring waters of high temperature and low volume also suggest dry steam at depth.

Chemical composition may also indicate the base, or maximum, temperature of a hyperthermal system. In Iceland, for example, it has been determined that the concentration of silica (SiO_2) in thermal waters is proportional to the base temperature at depth because of the increase in solubility of SiO_2 with temperature. In producing areas, high silica concentrations may cause serious problems of deposition in well bores. Healy (1961) believes that the ratios of certain constituents of thermal waters, such as chloride and silica, may show the possible duration and quantity of steam production.

One geochemical method that holds promise in prospecting for geothermal anomalies is the measurement of trace amounts of mercury, which exists as halos around most types of volcanic rocks and sulfide ore deposits. Williston (1964) states that because of its volatility, mercury vapor passes easily through water and thus can be a guide to submarine ore deposits. He also reports that in most instances, mercury abnormalities are associated with hot springs and that mercury might be helpful in determining the depth from which the hot water comes.

Geophysical Surveying. Numerous geophysical techniques give vital data in the three-dimensional evaluation of geothermal prospects. The first approach, of course, is the measurement of temperatures of springs and vents and the gauging of discharge from hot springs. This is ordinarily the prelude to a near-surface thermal survey to ascertain the extent of the anomaly in area and heat flow, done by recording temperatures in shallow drillholes laid out in an appropriate pattern. Usually a depth of 1 to 5 meters will suffice for rough contouring, although terrain, type of soil cover, and so forth may dictate greater depths.

Delineation of the anomaly will be greatly aided by heat-sensoring techniques now available. Infrared imagery, possible at great distances and altitudes, gives a vivid portrayal of electromagnetic radiation to which the human eye is insensitive, sharply contrasting even a low-temperature thermal area with its surroundings. Besides infrared photography, airborne radiometers are successfully used to record temperature profiles across anomalies. These methods are especially useful for reconnaissance and in rough or inaccessible regions.

Because rock resistivity is a function of temperature, decreasing as temperature increases, subnormal resistivity readings may be expected in thermal anomalies.

The magnetometer has been successful in delineating intrusive heat sources at depth, as much as 30 years ago in the Salton Sea area, and in defining the faults so critical in hyperthermal systems.

Likewise, gravity profiles are used to locate and define deep-seated intrusions and basement structures.

This, then, is the general state of the art of geothermal prospecting at the present time. Obviously, many valuable tools are available, and current research will undoubtedly provide the more sophisticated techniques as we progress to the search for more subtle anomalies.

GLOBAL CONTROLS AND REGIONS OF GEOTHERMAL POTENTIAL

Having examined the characteristics of geothermal areas and reviewed the conventional methods for evaluating them, let us broaden our horizons and apply these criteria and methods on a much larger scale.

Figure 1 shows worldwide areas of Cenozoic volcanic activity. Here we see the circum-Pacific belts, encompassing the west coasts of South and Central America, Mexico, Baja California, the West Coast of the United States, Alaska, the Aleutians, Kamchatka Peninsula, Japan, the Ryukyus, Philippines, Celebes, Marianas, New Britain, the Solomons, New Hebrides, Tonga, Kermadec, and New Zealand, as well as the intense belts through Java and Sumatra and in Manchuria; in East Africa, notice the volcanic trend in Tanganyika, Kenya, and Eritrea; in the Mediterranean region, the general alignment from Italy south into Libya; and finally, the well-known volcanism of Iceland on the mid-Atlantic ridge.

Figure 2 portrays the global distribution of active seismic belts. Well-known to seismologists, these areas encompass great trends along continental shelves, in mid-ocean regions, and certain continental land areas. Since seismic events result from either tectonic or volcanic phenomena, or a combination of both, it is not surprising to see much regional similarity between these figures.

Figure 3 depicts the mid-ocean ridge, or mountain range, that Heezen (1960) believes extends for 40,000 miles across the bottom of all the oceans and covers an area equal to that of all the continents. This mid-ocean ridge is severely rifted almost throughout its entirety and closely coincides

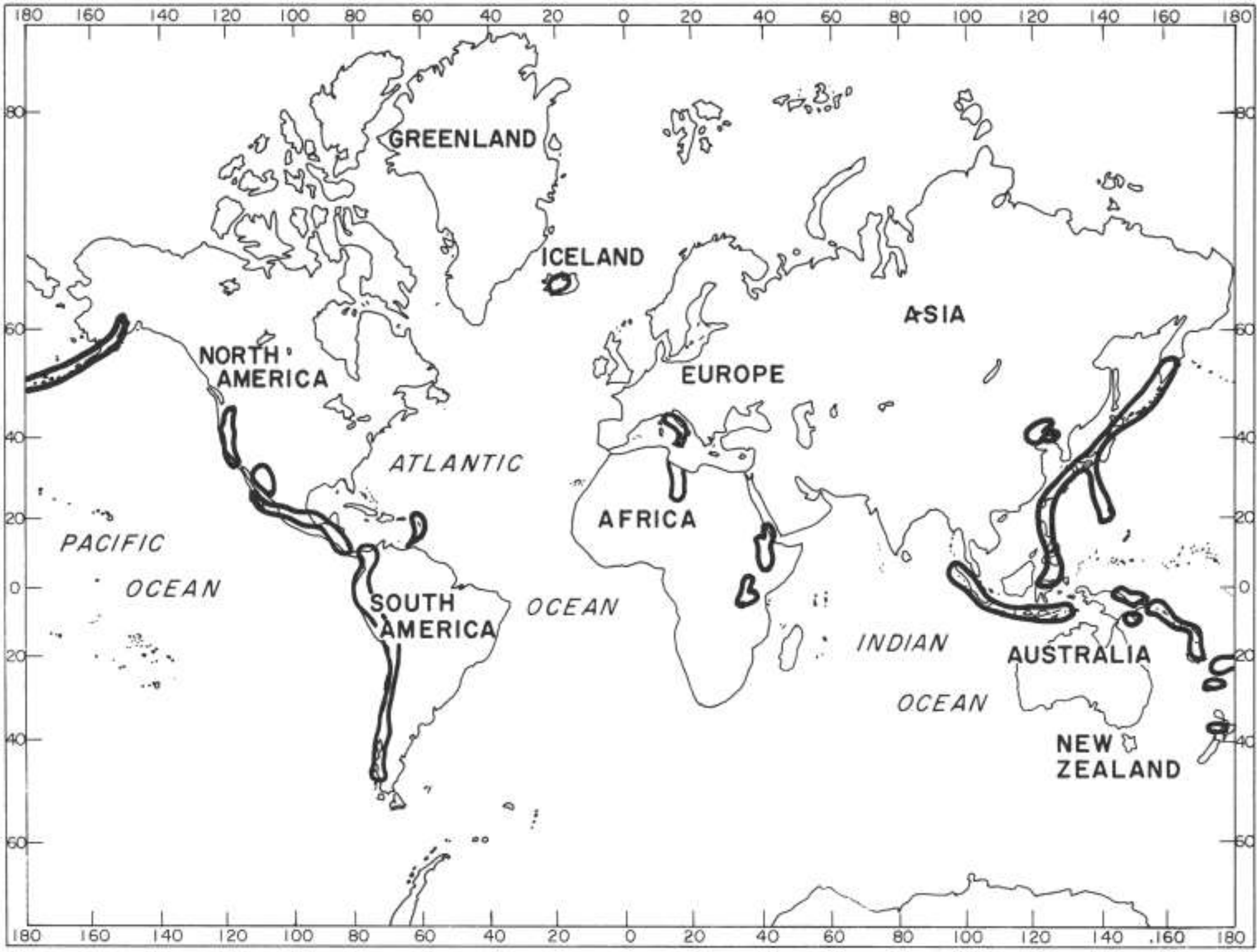

Figure 1
Areas of Cenozoic volcanic activity

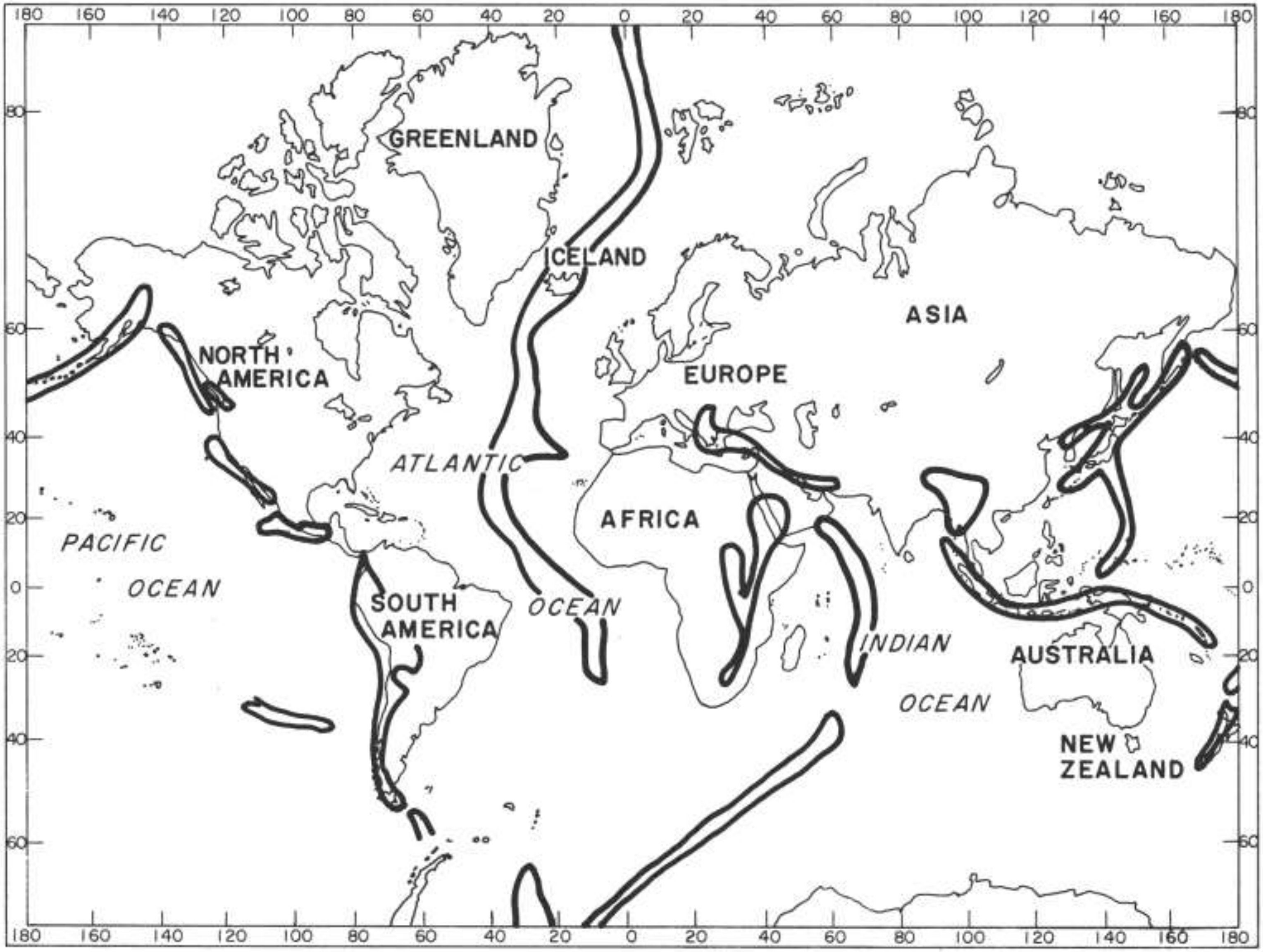

Figure 2
Areas of Global seismic activity (after kiersch)

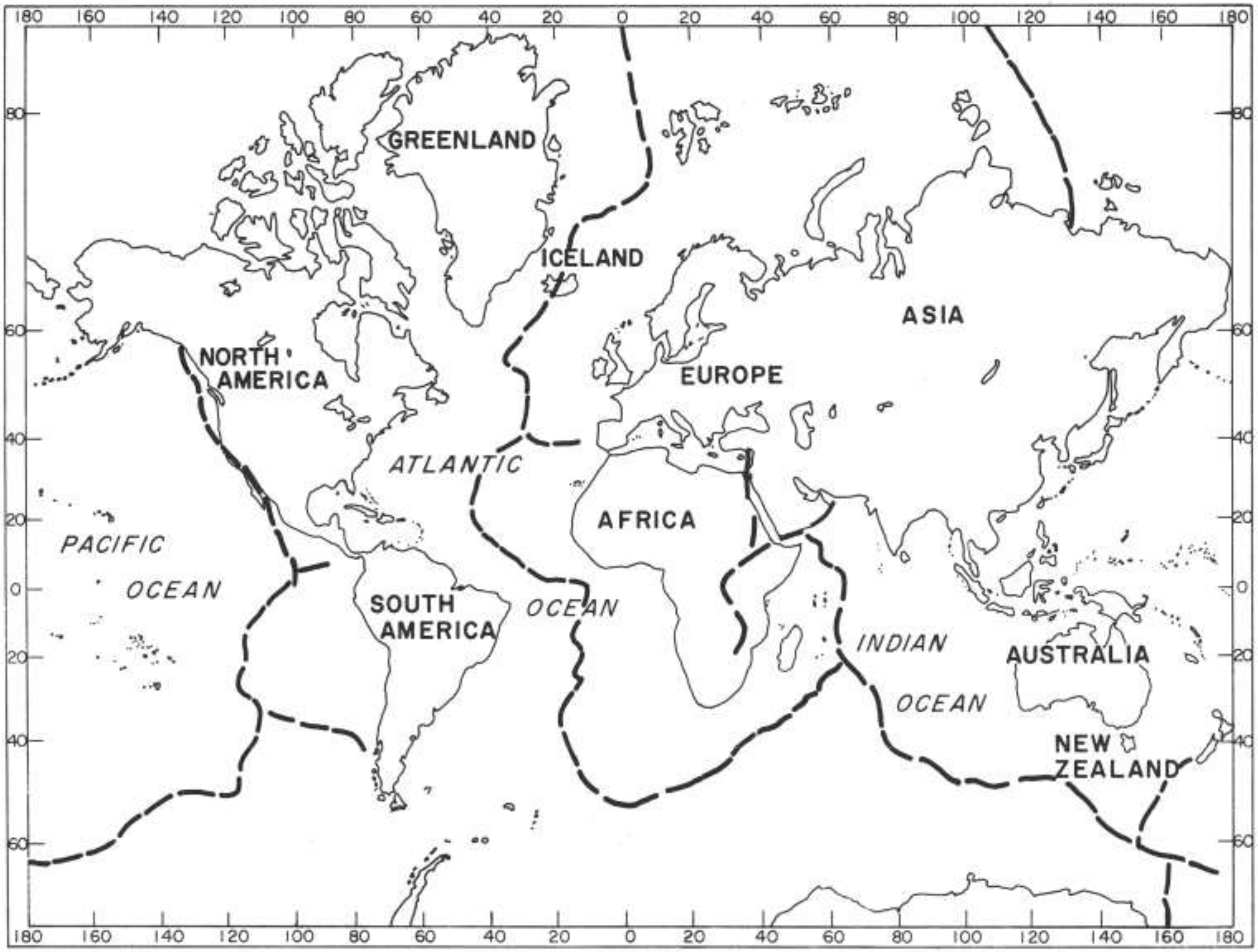

Figure 3
MID-OCEAN RIDGE (AFTER HEEZEAR)

with "a 40,000-mile-long belt of mid-ocean earthquake epicenters along the bottom of the Atlantic, Indian, South Pacific, and Arctic oceans, with branches reaching into the western Pacific and into the continents at several places," such as the rift valley system of the East African plateau. Heezen points out that the earthquakes of the mid-ocean ridge occur at the relatively shallow depth of 30 kilometers below the earth's surface, contrasting with the 700-kilometer-deep epicenters of the earthquakes surrounding the Pacific Ocean. This he attributes to expansion of the earth, supposedly due to a decrease of the gravitational constant in proportion to the age of the earth.

Finally, Figure 4, showing known hyperthermal districts of the world, graphically demonstrates a consanguinity with the volcanic and seismic belts that can hardly be fortuitous. While numerous geothermal areas are found outside the global volcano-tectonic belts illustrated, each of these other localities nevertheless is typified by the essential volcanic heat source and faulting.

Although the primary value of the foregoing slides is to illustrate the coincidence of volcanic and tectonic criteria in hyperthermal regions, this general approach, namely close comparison of trends of faulting with occurrences of heat source rocks, is basic, whether used in worldwide continental or undersea exploration or, on a smaller scale, to focus attention on worthwhile target areas of a given state or country.

EXAMPLES OF VOLCANO—TECTONIC CONTROLS

Utah and New Mexico

To bring these empirical observations into a more familiar frame of reference, let us briefly examine the volcano-tectonic relationship of known geothermal districts in Utah and New Mexico.

In Utah, hyperthermal occurrences are, for the most part, in proximity to that state's north-trending fault systems and are closely related to Quaternary and Tertiary igneous rocks (fig. 5). The principal trend follows the Sevier—San Pete—Wasatch lineament, while most of the remaining localities follow the Hurricane and other major faults in the western desert region. Naturally, the igneous rocks also appear in relative proximity to the thermal areas in these belts of structural weakness. To the south, in Arizona, no hot springs of commercial significance are known in the northern part of the state, much of which falls into the Colorado Plateau physiographic province. Rather, the majority of Arizona's geothermal occurrences are found in the central and southern parts of the state where the Paleozoic and Mesozoic crystalline and sedimentary rocks are covered by Tertiary volcanics, which probably accounts for the heat of most hot springs.

Let us glance briefly at Nevada's geothermal resources, which some might include under the title of this paper. Most of the state, of course, lies in the Basin and Range province, characterized by north-trending ranges of fault-block mountains separated by intermontane valleys. Nevada's hot springs, some of which will doubtless prove of economic importance, are widely distributed throughout the state. They nevertheless exhibit the usual gamut of favorable environmental criteria previously described, including, particularly, faulting and folding on sometimes grandiose scales in the proximity of Tertiary and Quaternary volcanics. We have already mentioned the unusual mineral assemblage found at Steamboat Hot Springs, south of Reno in the northwest part of the state, and the possibility that this and other localities may prove just as economically attractive because of the by-product minerals as the value of steam-generated electricity.

A similar environment occurs in New Mexico, where the Rio Grande structural trough, extending southward from Colorado to Texas, is the locus for the majority of thermal anomalies (fig. 6). Discontinuous fault zones form both the east and west margins of the trough, and Tertiary or Quaternary volcanic centers are usually in evidence close to the hyperthermal localities, which commonly lie along the west fringe of the trough. Most of the remaining thermal anomalies in New Mexico occupy similar but smaller structures west of the Rio Grande. One notable occurrence is the Valles caldera, one of the world's largest, west of Santa Fe. Following the accidental discovery of steam in an oil test well in 1960, three steam wells were drilled in the caldera, without the benefit of scientific counsel. Another accidental discovery has been made south of Lordsburg, where boiling water was encountered at depths of less than 100 feet in an area apparently devoid of nearby volcanism.

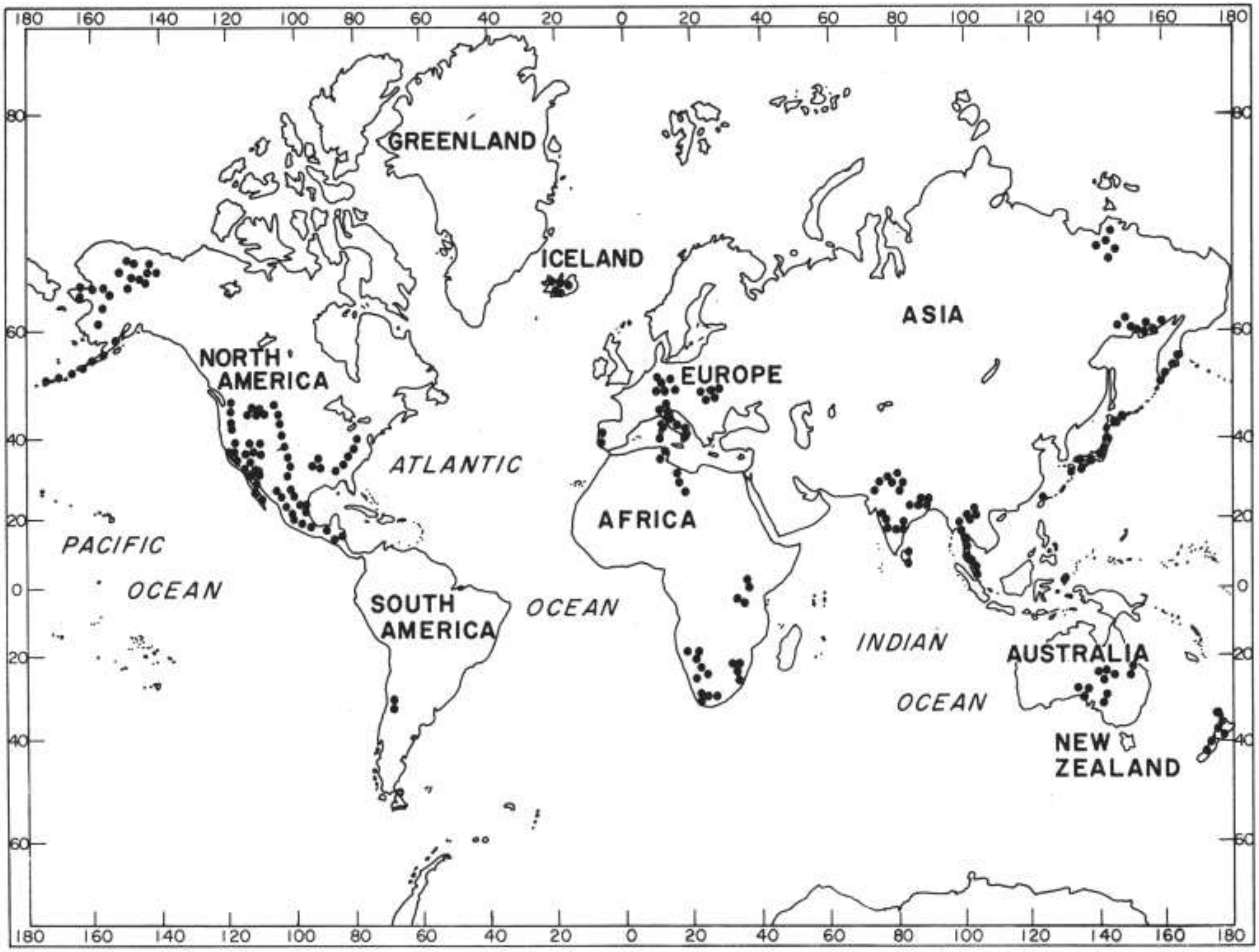

Figure 4
Areas of Hypothermal activity (after Kiersch)

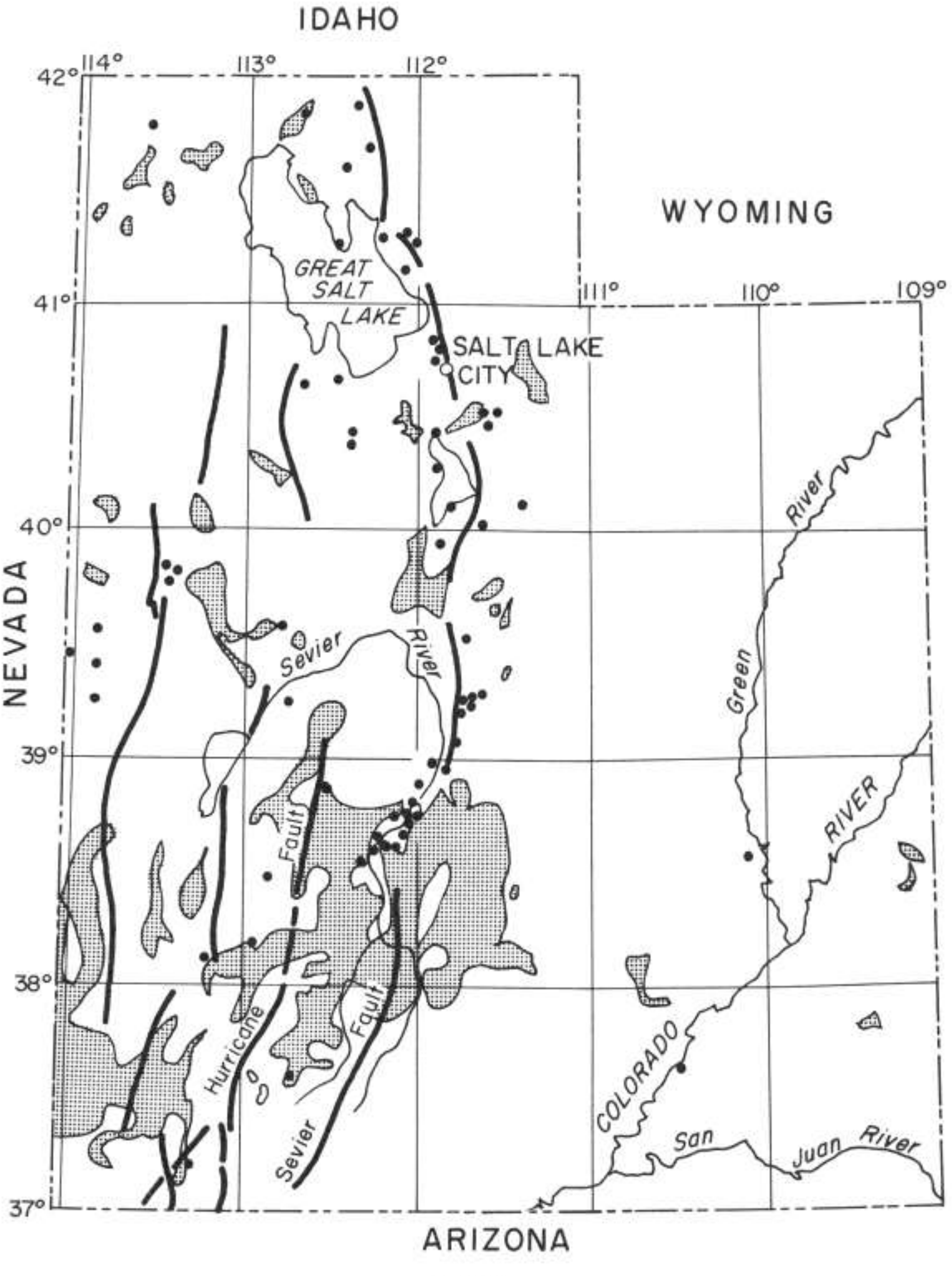

Figure 5
UTAH HYPERTHERMAL AREAS

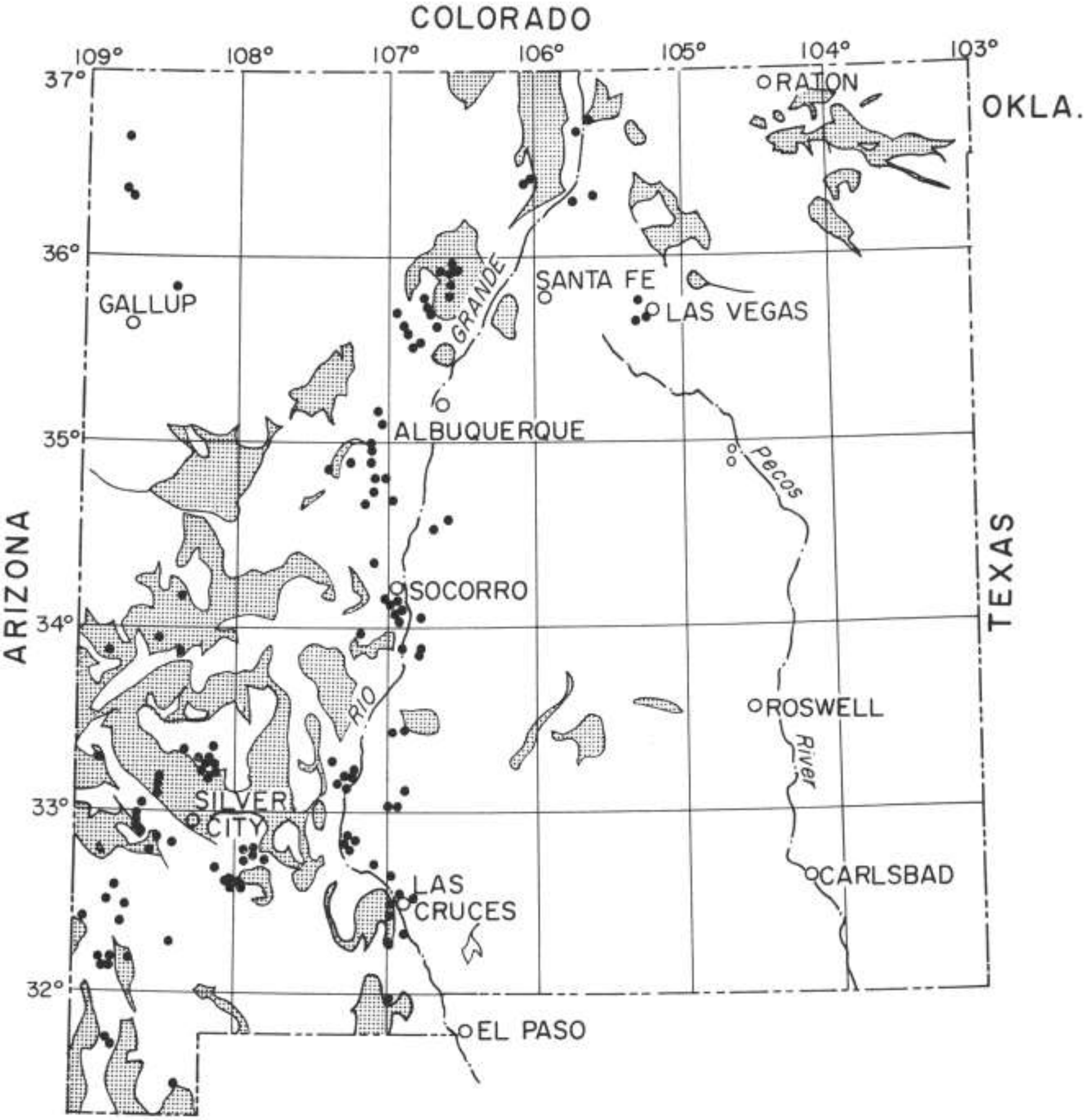

Figure 6
New Mexico Hyperthermal areas

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New Ideas in the Worldwide Exploration of Petroleum and Production of Petroleum

by James P. Malott
Continental Oil Company

ABSTRACT

New ideas and bold, exciting developments are before the petroleum exploration and producing segments of our industry today as never before in history. In this and the next decade, we will venture into the depths of the oceans to find and develop the petroleum resources of the world. We will apply nuclear energy, as in the Gasbuggy Project, to open new petroleum provinces to commercial development. We will automate our drilling machinery on land and at sea to an extent thought impossible only yesterday.

The exploration and production emphasis of the industry has been and will continue to be in foreign lands and offshore. These areas are the last frontiers where big money and big risk can still yield big rewards in cost per barrel of reserve discovered. Petroleum exploration money in the United States, as a result, is concentrated in offshore drilling.

Imaginative use of new scientific techniques, particularly in the search for stratigraphic and facies traps, will yield new discoveries, even in the heavily drilled interior regions. The recently developed Bell Creek field in Montana, similar in many aspects to northwest New Mexico's Bisti oil field, is a lucrative example of a facies trap. It was found by application of stratigraphic and sedimentation studies.

A New Concept for the Inducement of Underground Fracturing

by George B. Griswold
New Mexico Institute of Mining and Technology

For the past two years, New Mexico Tech has conducted research toward developing a means of creating gross fracturing of underground mineral deposits. If successful, the method would be applicable to improving oil and gas recovery from tight reservoirs, preparing lenticular deposits for in-place leaching, and fracturing coal beds for underground gasification.

At present, the only efficient method of forming large volumes of rubble underground is through the use of contained nuclear explosives. Large, thick deposits remote from population centers lend themselves to nuclear stimulation; for example, the recent Gasbuggy experiment conducted in northern New Mexico. But others are too close to populated areas, too shallow, or not of sufficient thickness.

Rubble formation depends on two factors, formative void space and holding that space open long enough for caving action to occur. A high-energy gas injection, the volume increasing exponentially with time, forms cracks that in turn are dilated if the injection volume exceeds the rate of crack spreading. Once sufficient area is uplifted, caving action starts.

Present experimental work is concentrated on heaving and bulking compacted copper leach dumps. From this simpler problem technology can be developed for tackling the hard-rock problem. The work is part of a joint effort of Tech, the U S. Bureau of Mines, and industry.

Blowdown Tunnel Demonstration

by Lamar M Kempton
New Mexico Institute of Mining and Technology

Two methods of providing experimental air flow by a target are flight tests and wind tunnels. Flight tests are seldom of a nature to allow for determination of the aerodynamic effects on the damaged target. In fact, in only a few instances can the actual damage to the target, which caused a certain result, be determined. In addition, flight tests are expensive (approximately $1 million each test).

Existing wind tunnels would not be suited to damage tests that require the firing of warhead-type devices because of the inherent danger to the tunnels. A "hard-construction type" blowdown device (preferably located within an existing field laboratory having a lethality/vulnerability program) therefore was seen to best meet the needs of the damage program.

First consideration for the construction of the Ballistics Effects Dynamic Data Device (BEDDD) was to bore a tunnel into the solid-rock hillside. However, further effort was made to locate suitable hardware existing in government excess, and the 23,000-gallon LOX containers of the Atlas Missile Sites near Roswell, New Mexico, proved ideally suited to the purpose of construction.

The BEDDD is designed to provide for the simulation of the in-flight dynamic characteristics of air targets. Data for tests on the ground of these air targets are nearly the sole source for estimates in the vulnerability/lethality programs for air targets. However, ground tests at New Mexico Tech cannot include measurements of the effects of aerodynamics upon damaged air-targets until the air flow rate of BEDDD can be made available.

In the current procedure for damage assessment, staff members of the damage programs predict the response of air targets to inflicted damage with little or no actual dynamic data to support their predictions.

Distribution and Abundance of Mercury and Other Trace Elements in Several Base- and Precious-Metal Mining Districts

by J.H. McCarthy, Jr., Garland B. Gott,
and W W. Vaughn
U.S. Geological Survey, Denver, Colorado

Because mercury anomalies have been found in the soil and rock around many ore deposits, the usefulness of mercury as an indicator for ores has been established (Erickson et al., 1966; Gott and McCarthy, 1966; Gott et al., 1967; Hawkes and Williston, 1962; James and Webb, 1964; Ozerova, 1962). In this report, the distribution of mercury in rocks or soils of four base- and precious-metal mining districts is illustrated and. compared with the distribution of other elements. Recent experiments to measure mercury in the atmosphere, also described, indicate that the mercury contents of soil gas and air may also prove valuable exploration tools.

MERCURY IN ROCKS AND SOILS

Two base-metal deposits were studied: one, the porphyry copper deposit in the Robinson district, near Ely, Nevada; the other, the lead-zinc-silver deposit in the Park City district, near Salt Lake City, Utah. The two precious-metal deposits investigated were those of Cripple Creek and of Lenado (near Aspen), Colorado.

The Robinson district is one of the major copper-producing areas in the western United States (Bauer et al., 1966). The deposits are associated with a quartz monzonite body emplaced in Paleozoic limestones. An aeromagnetic survey showed that the monzonite causes a large magnetic high. The survey (Carlson and Mabey, 1963) also revealed another magnetic high 12 miles to the south. The similarity of these anomalies suggests that both are caused by large intrusive masses connected at depth. Alteration and silicification along faults in the Rowe Canyon area suggest that the postulated southern intrusive mass is also mineralized. To investigate this possibility, a geochemical survey was made over the southern magnetic anomaly, and, to obtain comparative data, a geochemical survey was made over the known copper deposits to the north. Approximately 1500 surface-rock samples were collected in these areas.

The Park City district lies in the Wasatch Mountains 25 miles southeast of Salt Lake City. The ore occurs in vein and replacement deposits in sedimentary and intrusive rocks. The ore minerals are lead, zinc, silver, and minor amounts of copper and gold. Approximately 1300 soil samples were collected in the district.

The famous Cripple Creek mining district 20 miles southwest of Colorado Springs has produced about 21 million ounces of gold since its discovery in 1891 (Laughlin and Koschmann, 1935). The gold deposits are largely confined to a roughly elliptical volcanic subsidence basin about 4 miles long and 2 to 3 miles wide that is surrounded by Precambrian granite and metamorphic rocks. The basin is filled with fractured and brecciated volcanic rock, chiefly latite-phonolite and phonolite. The major fracture systems trend generally north in the basin, and it is in these that the gold telluride ores, the principal ore minerals, were localized. For this study, approximately 500 rock samples were collected from the dumps of shallow prospect pits that had been dug to bedrock.

The Lenado district near Aspen has produced lead, zinc, and silver—the silver usually being associated with galena. Ore has been found along the Lenado fault at the contact of the Pennsylvanian Belden Shale and the Mississippian Leadville Limestone, but some ore has been found along the silver fault. The area is largely covered by colluvium, and the valleys are filled with alluvium or glacial till. For this study, approximately 250 soil samples were collected in the district.

Geochemical Anomalies

The geochemical anomalies in the Robinson district show that several elements outline the district and are enriched in different zones. Copper is most abundant in the central core and is surrounded by a zone in which lead, zinc, mercury, tellurium, arsenic, antimony, silver, and gold are most concentrated.

The distribution of mercury is shown in Figure 1. The concentration of mercury is low in the central copper core and is enriched in an envelope partly enclosing it. Background concentrations of mercury outside the mineralized area are 10 to 30 ppb (parts per billion). The samples containing more than 100 ppb mercury form a halo that defines the whole district. Of particular note is a narrow zone that partly surrounds the copper core in which mercury is concentrated in the range 1000 to 5000 ppb.

Tellurium shows a similar, yet wider, distribution pattern than that of mercury. Its relative enrichment is greater, however, as shown by one sample that contained 1 percent Te, an enrichment of 5 million times over its crustal abundance.

Erosion has removed most of the rocks that originally concealed the deposits. Before removal of this roof, the volatile elements concentrated in a zone peripheral to the

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***Publication authorized by the Director, U.S. Geological Survey.**

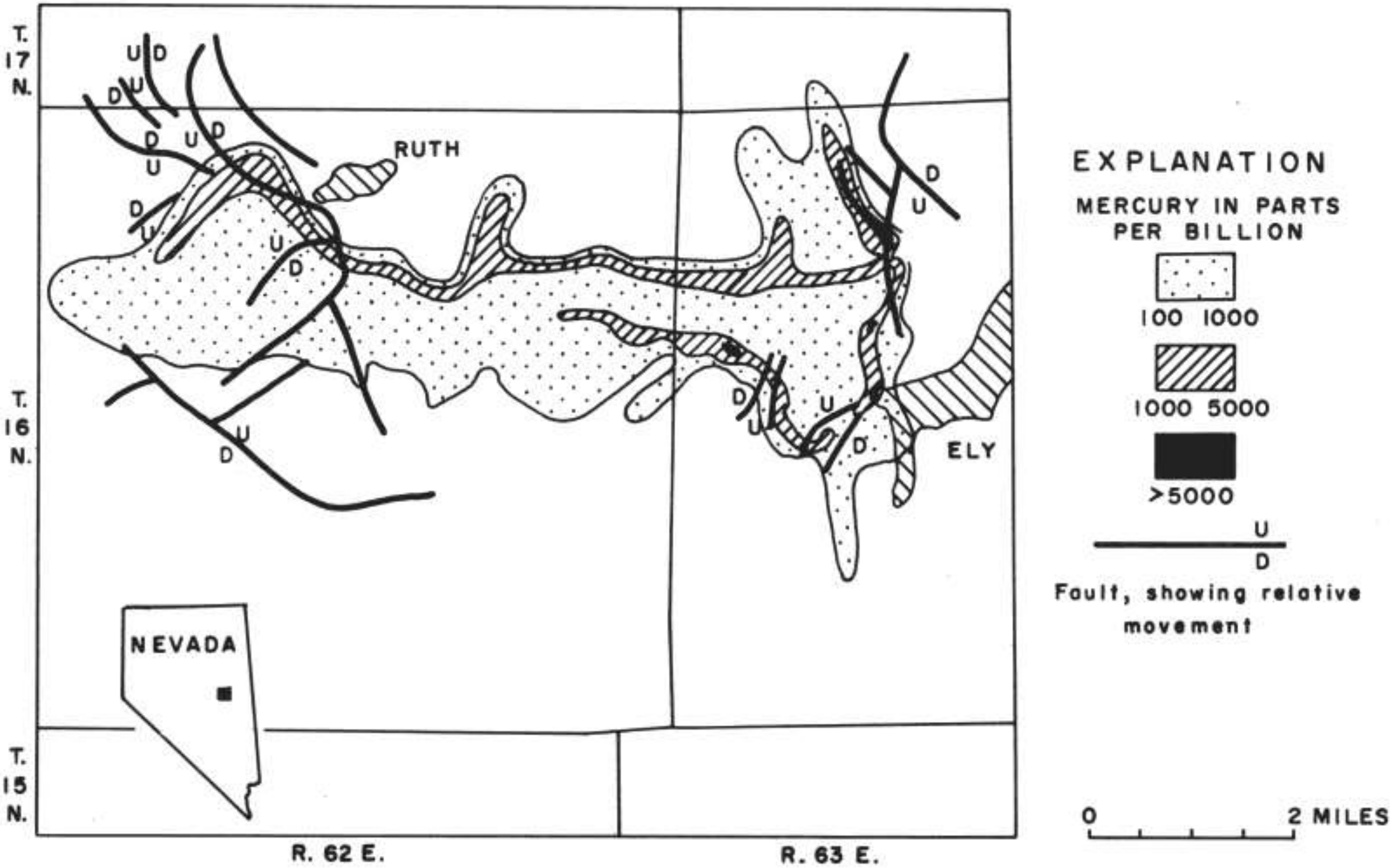

Figure 1
Distribution of Mercury in rocks in the Robinson Mining District, White Pine County, Nevada

center of mineralization probably bent upward and over the central mineralized core. If the cover were thick enough, only the more mobile elements would have penetrated to the surface.

In the Rowe Canyon area, south of Ely, geologic mapping (Brokaw et al., 1962) revealed mineralized rock along some faults. The aeromagnetic survey indicates that the top of the main instrusive mass, which causes the magnetic anomaly in the Rowe Canyon area, may be as deep as 3000 feet. However, small stocks extending upward from the main intrusive body could be present and would not have been detected by the aeromagnetic survey. In this area, anomalous concentrations of the more mobile elements might be expected in the surface rocks, but high concentrations of the less mobile elements, such as copper, lead, and zinc, would not be expected. A geochemical survey revealed this interpretation for the area to be true. Small anomalies of copper, lead, and zinc were found but were weak and restricted. The distribution of mercury (fig. 2) is extensive, and the content of mercury is highest along the faults. The silver anomaly is more restricted than that of mercury, but the pattern is similar. The distribution of tellurium is more extensive than that of either mercury or silver and illustrates its high mobility. These geochemical anomalies are probably leakage halos derived from a mineralized source at depth.

In the Park City district, the distribution of lead and zinc in soils reflects the mineralized zones indicated by Boutwell (1912). The mercury anomaly also coincides with these zones but is more extensive (fig. 3). The extent of the silver anomaly is greater than that of any of the elements investigated. The enrichment of silver is also striking—one soil sample contained 300 ppm.

In the Cripple Creek district, mercury is concentrated only in the areas of highest gold content, and it does not give so extensive a geochemical pattern as does either gold or silver (fig. 4). The areal extent of the tellurium anomaly is larger than that of the gold or silver (Gott et al.).

In the Lenado district, the distribution of lead, zinc, and silver reflects the known mineralized areas, and all give similar distribution patterns (McCarthy and Gott, 1966).

The distribution of mercury (fig. 5) is somewhat patchy. The areas of highest mercury content in the soils reflect the known mineralized areas but do not extend beyond them. The mercury in this district was less abundant than in the other three districts.

Conclusions about the use of mercury in geochemical exploration, drawn from the rock and soil sampling in these four districts, include the following:

1. Mercury is more abundant in the rocks and soils of the two base-metal deposits than in the precious-metal deposits. The average mercury concentration in parts per million is, for the Robinson district (rocks), 1.8; Rowe Canyon (rocks), 0.61; Park City (soils), 0.41; Cripple Creek (rocks), 0.19; and Lenado (soils), 0.04.
2. Mercury anomalies reflect the known mineral deposits in all districts, but other elements give larger targets in some places.
3. Mercury might be used to indicate the presence of concealed mineral deposits and perhaps even their depth, if the mercury is zoned as clearly as it is in the porphyry copper deposit at Ely.

MERCURY IN SOIL GAS AND AIR

Recognition of the high vapor pressure of mercury leads to the assumption that a source of mercury at depth would release mercury vapor that might be detected in the soil gas and air above such a source. This assumption led us to investigate the mercury content of soil gas and air to test the possibility that the content might prove a useful guide to buried mineral deposits.

Apparatus and Technique for Measuring Mercury in Soil and Gas

Pyramidal tents of transparent plastic funneled soil gas through gold or silver foil to trap mercury (McCarthy et al., 1969). A tent placed on the ground and soil banked around its base excluded free movement of air into it from the outside. Gold or silver flakes (about 1 g) were spread evenly in a stainless steel wire-mesh basket placed over an opening in the top of the tent. Solar heat raised the temperature in the tent, setting up convection currents that carried the air in the tent upward through the trap. Several tents were placed along a traverse and left in position for 2 hours. The traps were then collected and analyzed for mercury content.

Ground Experiments. The recently discovered gold deposit at Cortez, Nevada, was chosen for study because rocks in the area contain anomalous concentrations of mercury closely associated with the gold Erickson et al.). Much of the area is covered by alluvial gravel. Measurements of mercury in soil gas were undertaken to determine (1) if measurable amounts of mercury vapor from the gold deposit were migrating through the gravel into the atmosphere and (2) if a significant difference existed between the mercury content of soil gas over barren bedrock and that over gold-bearing bedrock. The results of this study show that greater amounts of mercury in the soil gas were found in the areas known to contain gold and that the configuration of the mercury anomaly is similar to the configuration of the gold deposit in the bedrock (fig. 6).

Soil samples taken at each tent locality show that the mercury content of the soil does not reflect the known gold deposit so well as the mercury content of the soil gas. The conformity of the soil gas anomaly to known mineralized bedrock suggests that the mercury was derived from bedrock.

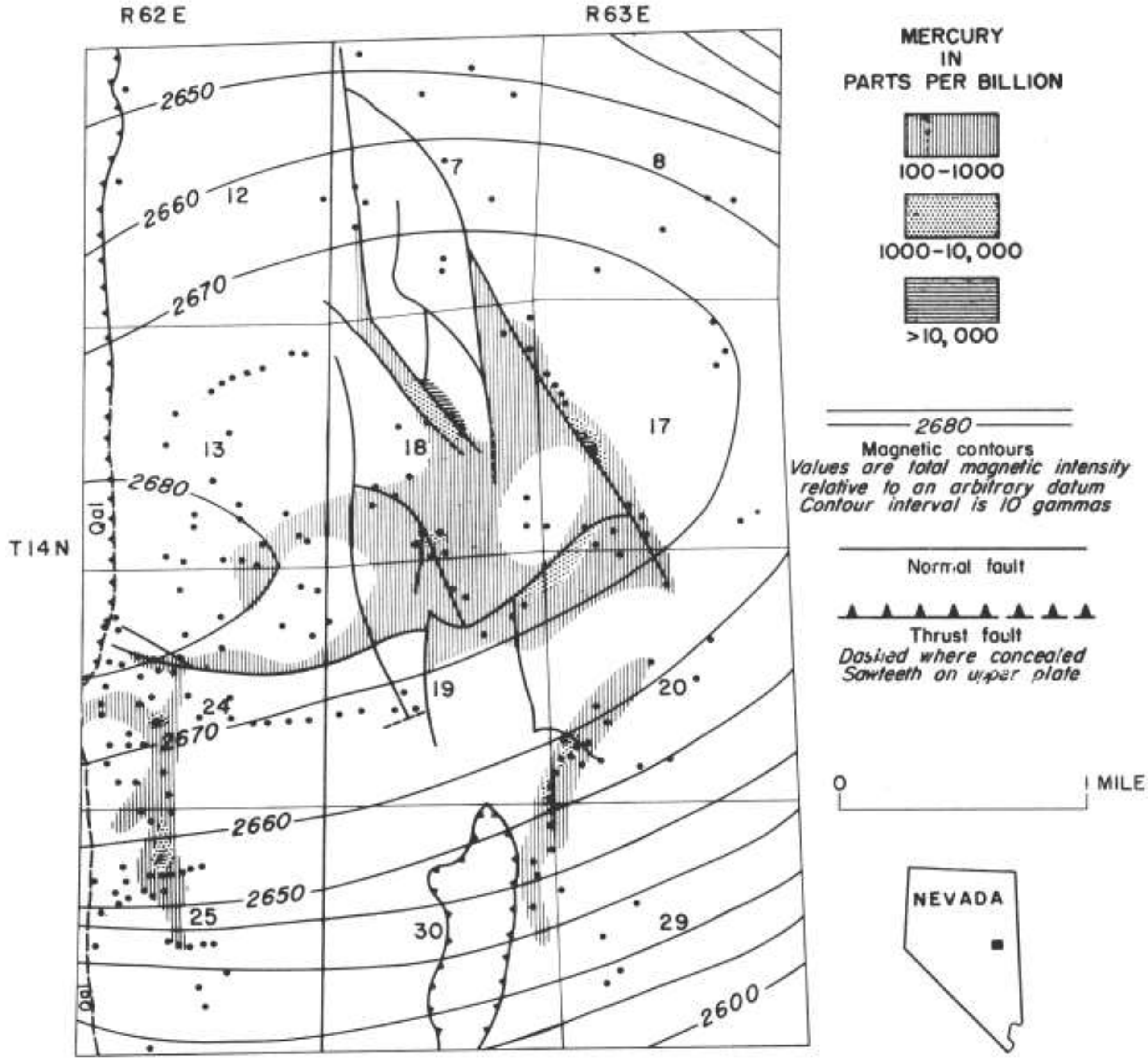

Figure 2
DISTRIBUTION OF MERCURY IN ROCKS IN THE ROWE CANYON AREA, WHITE PINE COUNTY, NEVADA
Dots indicate sample localities.

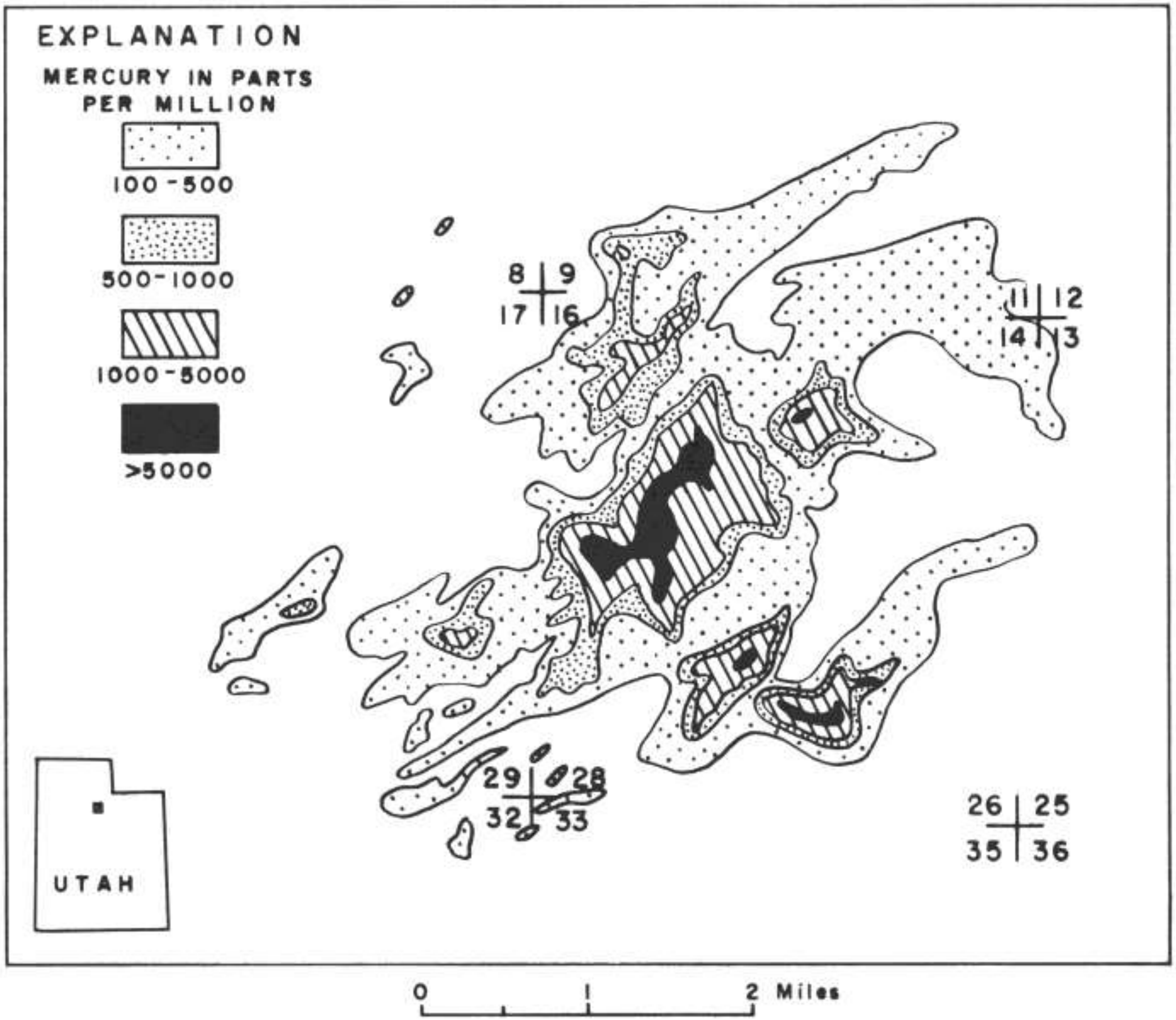

Figure 3
Distribution of Mercury in soils of the Park City District, Summit and Wasatch Counties, Utah

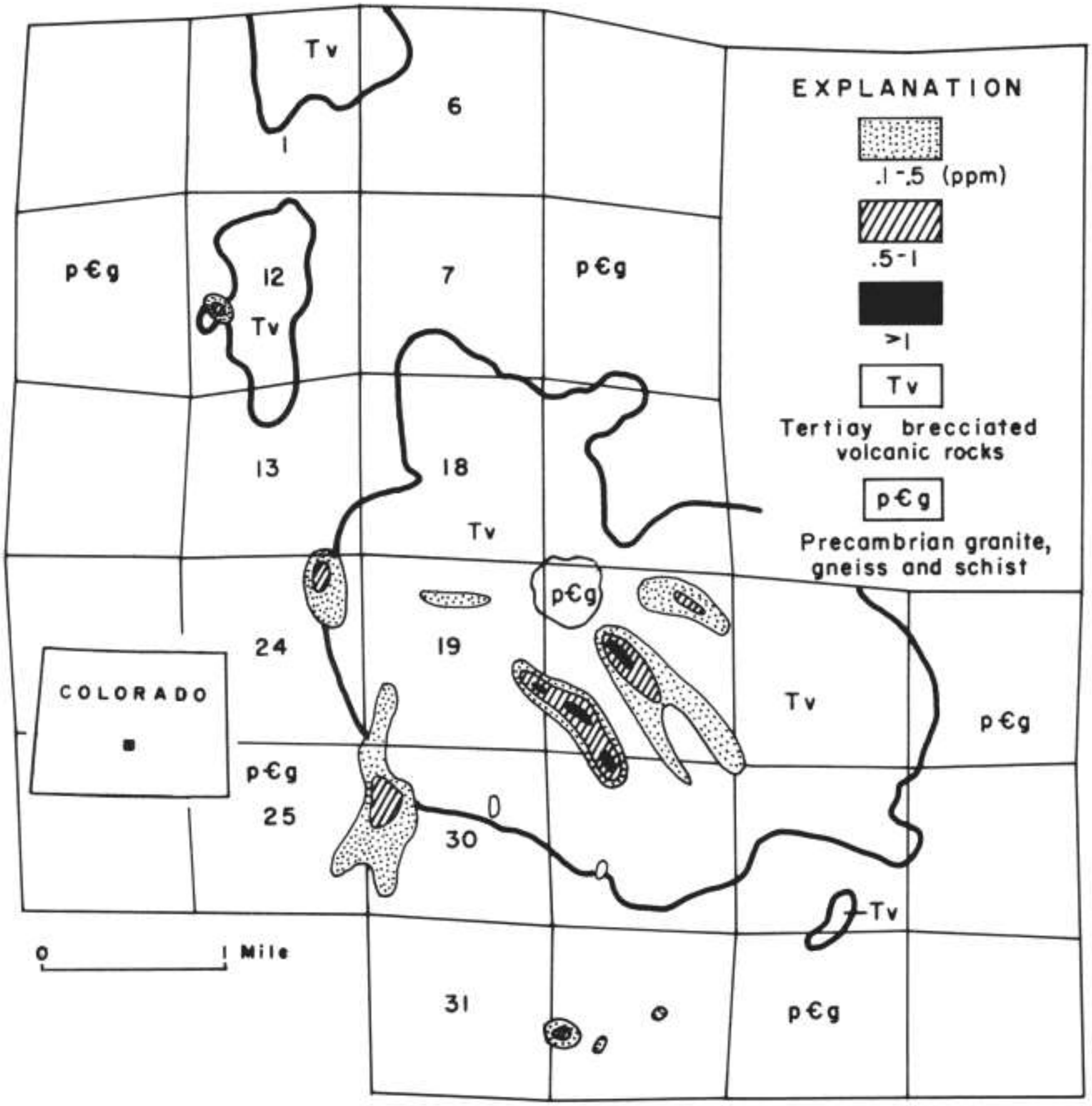

Figure 4
Distribution of Mercury in rocks in the Cripple Creek District, Colorado

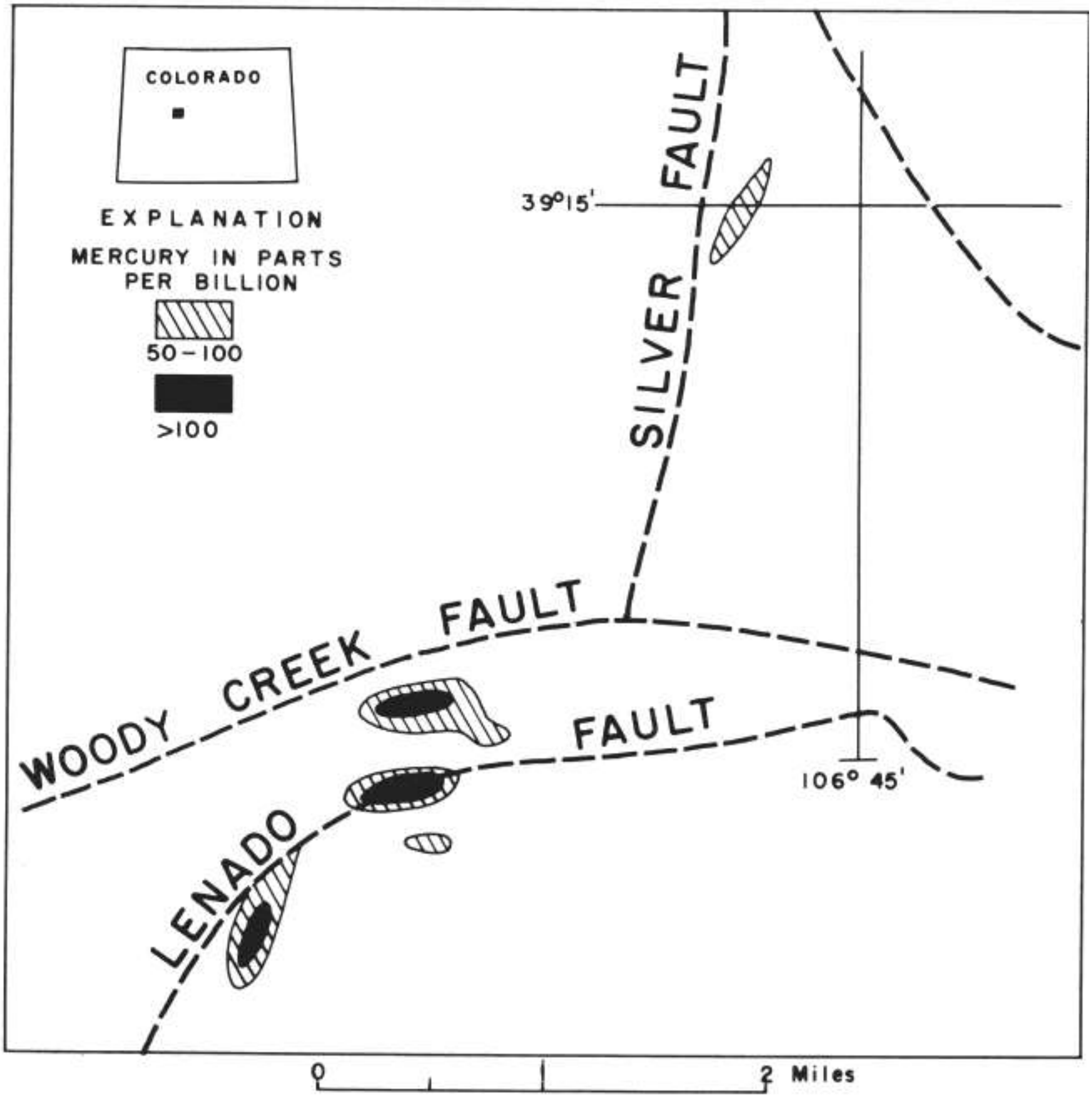

Figure 5
Distribution of Mercury in soils in the Lenado District, Pitkin County, Colorado

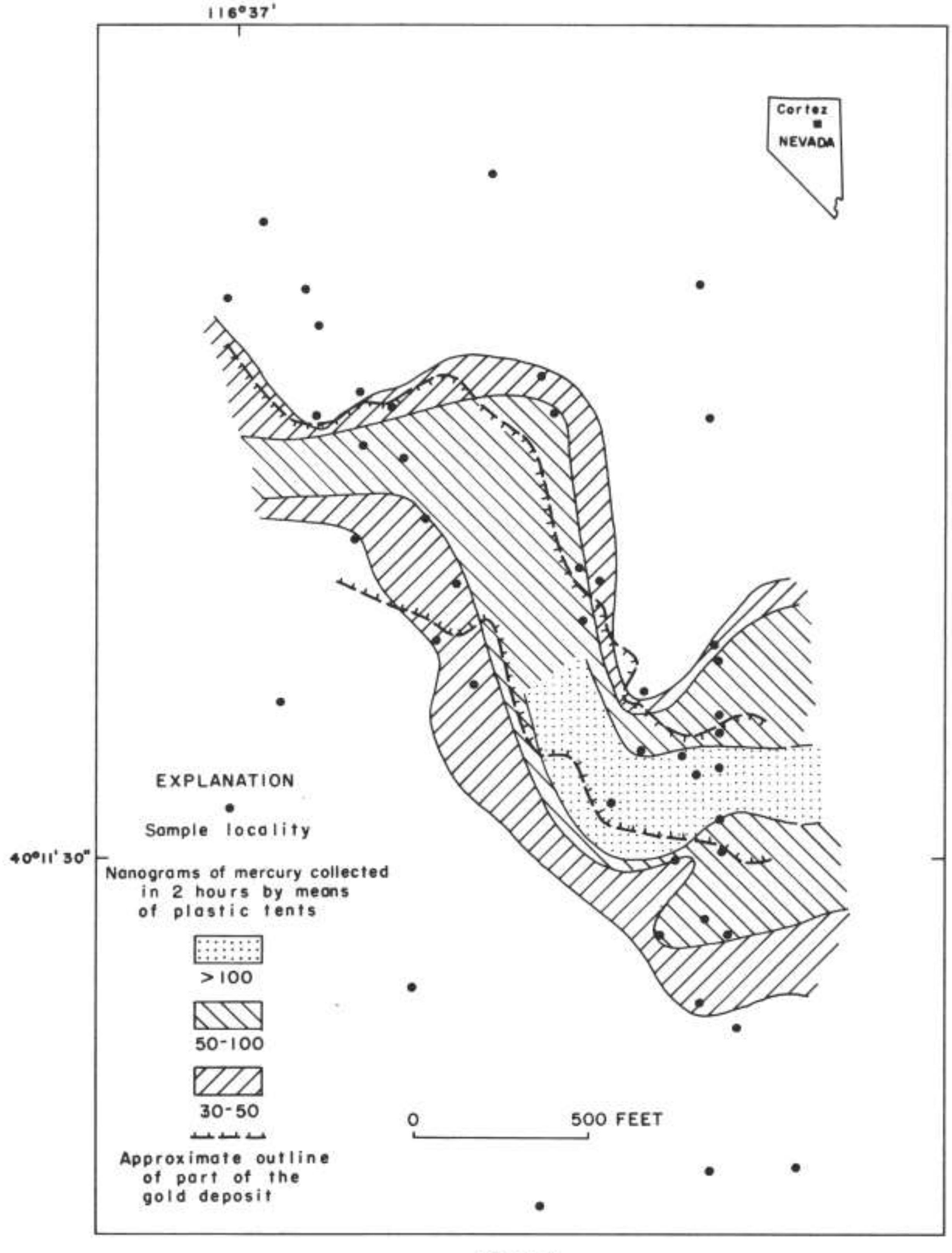

Figure 6
Mercury in soil gas at the Cortez gold deposit, Lander and Eureka Counties, Nevada

The relation between the mercury content in several soil-gas samples and barometric pressure at the time of collection was studied. Although insufficient data have been collected clearly to demonstrate the dependence of the amount of mercury in soil gas on change in barometric pressure, the available data suggest that the maximum amount of mercury is collected about midday, a period corresponding to the maximum rate of fall in barometric pressure.

The effect of the thickness of overburden on soil-gas measurements was also investigated in the Cortez area. As much as 100 feet of gravel cover the mineralized bedrock; however, this thickness of overburden did not seem to hamper the movement of mercury to the surface.

Apparatus and Technique for Measuring Mercury in Air

If it could be demonstrated that mercury vapor occurred in the above-surface air, it might make possible the collection of mercury in air from ground-based vehicles or aircraft and greatly broaden the potential application of this technique. Air sampling was done from a moving vehicle along a 40-mile traverse through the Ivanhoe mercury district, about 40 miles northeast of Battle Mountain in Nevada. The highest values were found over the area of known mercury production.

Aircraft Experiments. Because significant quantities of mercury had been found in air above the surface of the ground, additional experiments were conducted to determine (1) the altitude to which mercury ascends in air and (2) the correlation, if any, of mercury in air at higher altitudes with known mineral deposits.

An intake tube was installed in a single-engine Beaver aircraft to bring air inside the cabin, and a measured volume of this air was passed through noble-metal foil traps. To determine the optimum altitude for mercury collection, air was collected at altitudes from 100 to 1000 feet. As a result of these data, which showed a tapering off of mercury at about 200 feet, all the flying in these experiments was done at an altitude of 200 feet.

Mercury in air was measured in Arizona over two mercury deposits (in the Superstition Mountains and Dome Rock Mountains) and over two porphyry copper deposits (the Ajo and Silver Bell pits); the data obtained are summarized in Table 1. Air collected over the two mercury deposits contained 10 to 20 times more mercury than that in background air. At Ajo, the greatest concentration of mercury collected (30 nanograms per cubic meter) was over the edge of the mine pit and may suggest peripheral enrichment of mercury. Higher concentrations of mercury were found in air over the open pits at Silver Bell than over those at Ajo. Several longer traverses were flown along the highway from Quartzsite, Arizona, to the Colorado River at Blythe, California, to determine the background concentration of mercury in air (table 1). At both copper deposits, the mercury in air was 5 to 10 times higher than that concentrated in background air.

TABLE 1. SUMMARY OF DATA ON MERCURY CONTENT IN AIR
(collection made by means of aircraft; all figures in nanograms per cubic meter)

AREA	MIN.	MAX.	AVE.
Superstition Mountains	58.0	66.0	62.0
Dome Rock Mountains	12.0	57.5	31.4
Ajo	12.0	30.0	18.8
Silver Bell	18.5	53.2	27.6
Colorado River at Blythe, Cal., to Quartzsite, Ariz.*	1.6	7.2	4.5

*Background concentration.

SIGNIFICANCE OF MERCURY IN SOIL GAS AND AIR

Occurrence of dispersion halos, which reflect mineralized rock, is usually limited to bedrock or residual overburden. If, however, the overburden is permeable to the passage of mercury vapor, the measurement of mercury in soil gas or air may be a reliable indicator of concealed mineral deposits in bedrock. The nature of the overburden and perhaps even its thickness may be of minor importance.

This technique might be successfully used to investigate the mineral potential of pediments in the Basin and Range province or of the vast areas of the west that are overlain by volcanic rocks or alluvium.

The use of an aircraft to detect mercury may make it possible to explore large and inaccessible areas rapidly. It may be possible to delineate or to extend metallogenic provinces by means of mercury zoning or to detect new large, regional mineral belts or trends, particularly if the data obtained by mercury zoning are used in conjunction with regional geophysical data.

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Air- and Space-Borne Remote Sensors for Mineral Exploration

by W. D. Carter
U.S. Geological Survey
Washington, D. C.

In 1964, the National Aeronautics and Space Administration invited the U.S. Geological Survey, Department of Agriculture, and Naval Oceanographic Office to join it in establishing an earth-looking, space-applications program. The program was designed to determine how space vehicles, manned or unmanned and equipped with remote sensors, might effectively be used in the discovery, monitoring, management, or conservation of earth resources. The Department of Agriculture was appropriately given prime responsibility in the fields of agronomy and forestry. The Naval Oceanographic Office was given prime responsibility for marine applications, and the Geological Survey was asked to provide leadership in the fields of geology, hydrology, geography, and cartography. The program developed slowly, with the establishemnt of a number of test sites or field areas for each of the disciplines involved and where experiments in ground mapping and monitoring were conducted in conjunction with remote-sensor-aircraft overflights. In addition, experience was gained in the use of space data such as Gemini and Mercury color photography, Nimbus and Tiros vidicon photography, and Nimbus infrared imagery. The preliminary results of these investigations were sufficiently encouraging for Secretary Stewart Udall to announce in September 1966 that the Department of the Interior would embark on a concerted investigative effort called the Earth Resources Observation Satellite (EROS) Program. He named the Geological Survey as primary bureau in the program. Currently, more than ten bureaus within the Department are assessing potential applications and benefits and are initiating feasibility studies, where necessary. They include the bureaus of Mines, Commercial Fisheries, Land Management, Reclamation, Outdoor Recreation, Sports Fisheries, Indian Affairs, and the National Park Service.

Since Secretary Udall's announcement, the Department has presented NASA with the specifications for an initial Earth Resources Satellite. It is a lightweight, relatively inexpensive, unmanned vehicle carrying three high-resolution television cameras and a data relay system. It will fly in a near-polar, sun-synchronous, and circular orbit about 500 miles above the earth's surface. The multispectral photographs acquired will cover about 100 miles on a side and have resolutions of about 150 feet; that is, objects having 150-foot dimensions or larger and 2 to 1 contrast with their backgrounds will be visible. Sun synchronism with inclined solar illumination will provide sufficient shadow for terrain interpretation, yet not mask other details of interest. The three cameras will provide simultaneous multispectral photographs at 530, 650, and 750 millimicrons, respectively. Therefore, in addition to providing synoptic views of large areas, they will permit observations on the location and relative vigor of vegetation, the distribution of moisture in soils, and observation of shallow subaqueous bottom features, as in lakes, estuaries, bays, and nearshore marine areas.

A recent study of potential monetary benefits, conducted by the Westinghouse Corporation under contract with the Interior Department, revealed many areas of potential benefit but only a few to which reasonable monetary figures could be assigned. In spite of this, the estimate for the Interior Department was on the order of $80 million a year. Major areas of saving were increased knowledge of range conditions on public lands and better knowledge of water distribution and irrigation practices that could lead to better water management and improved conservation methods.

You might find it interesting to know that the total annual budget of the Interior Department is approximately $1.5 billion a year. Revenues from public lands, in the form of royalties, mineral leases, and so forth, contribute approximately $1.2 billion to the U.S. Treasury. Since the public lands are administered by agencies of the Interior Department, the Department is nearly self-sustaining. Savings of the type envisioned as gained by the use of space data should help all government agencies become more cost-efficient and help reduce our ever growing tax burdens.

Projection of these estimates into the private sector indicated benefits of as much as ten times as great. Of course, it will be years after such a satellite is orbited before we can truly assess the practical benefits and weigh them against actual costs. At this time, however, I invite members of industrial firms at this conference to study our proposal in greater detail and make your own estimates of its potential value to your efforts.

I would like to turn now to a brief discussion of our Geologic Applications Program, under which we are conducting feasibility studies of remote sensing as applied to geologic problems in general and to mineral resource problems in particular. I will discuss the objectives and methods we are using, then list a few of the more significant results, placing emphasis, where possible, on studies that have been conducted in the Southwest and that I think are most pertinent to your problems and areas of interest.

*** Publication authorized by the Director, U.S. Geological Survey.**

OBJECTIVES

Objectives of the Geologic Applications Program are to

- define the types of geologic problems that can be assisted by remote sensing techniques from air-and spacecraft;
- determine which of the remote sensors best facilitates solution of the problems defined; and
- design conduct experiments to test the feasibility of solving or assisting in the solution of problems selected by remote sensing from air- and spacecraft.

METHODS

Studies undertaken within the Geologic Applications Program can be divided into four major categories, as follows:

Empirical investigations of airborne-sensor data acquired over selected sites presenting a variety of geologic conditions or problems; for example, Yellowstone National Park, Wyoming; San Andreas fault, California; Oregon/Washington coast; Carlin, Nevada. Under these studies, we have also evaluated Gemini and Nimbus space photography and infrared imagery.

Instrument investigations involve the development of remote sensor instruments for geologic investigations or the modification of existing instruments or supporting ground equipment. Examples of investigations currently under way include measurements of ultraviolet reflectance and stimulated luminescence and the development of an instrument called a Fraunhofer line discriminator to be used to detect fluorescent dyes (W. **R.** Hemphill, U.S. Geological Survey). Efforts in the infrared field have been devoted largely to developing useful ground monitoring equipment to assist infrared image interpretation. The objective has been to increase the geologist's ability to observe large areas at one time by using multiple thermistor arrays automatically recorded in sequence prior to, during, and after infrared aircraft missions **(R.** M. Moxham et al., U.S. Geological Survey).

Theoretical investigations into the physical and chemical laws fundamental to a thorough understanding of remote sensors and their reactions to nature materials are being conducted in our laboratories in Flagstaff, Arizona. These studies begin with pure materials, such as quartz, to determine how chemical and physical parameters such as crystal structure, grain size, porosity, and moisture content affect various types of remote sensor records. Test sites to be studied from aircraft include glass sands at Mill Creek, Oklahoma, and quartzose dune sands at Grand Sable, Michigan. We hope that standards can be established against which remote sensor data can be compared to facilitate interpretation and understanding of such data.

Benefits investigations to determine the relative merits and cutoff points of relaying earthquake data via satellite have recently begun. What quantities of data can be relayed by satellite systems? Can data from seismographs, strain gauges, and tilt meters be reduced and transmitted economically? What are the economic cutoffs in using telephone lines, ground-based microwave systems, and satellite relay systems? How much must data be reduced or filtered to be accepted by radio and telemeter systems?

RESULTS

Although the program has probably raised as many new questions as it has answered to date, it has produced some noteworthy results. I would like to enumerate just a few of them and attempt to provide a few examples that support these findings.

Synoptic views from space can provide a new and up-to-date base for direct synthesis of many types of regional studies. They permit inductive reasoning by enabling the geoscientist to see a whole scene first, then focus on specific targets of interest. This is especially useful in remote areas of the world where access is difficult and high costs and time are important factors in mineral exploration.

A space photograph of Kerman, Iran, taken by Gemini astronauts, shows that low sun angle can enhance geologic features, such as folds and faults, that interest the exploration geologist, especially one involved in search for petroleum resources. A similar photograph of the Tucson, Arizona, area from Gemini photography and the most recent Apollo mission showed fault and fracture patterns and color variations in the land surface never clearly recognized before. Some appear similar in tone to alteration zones often associated with porphyry-type copper deposits.

We have put a series of such photographs together as mosaics. One of Peru and vicinity covered most of the northern Andes and revealed lineaments several hundreds of miles long paralleling the Toquepala and Cerro de Pasco mining districts. Another of the southwestern United States, covering 250,000 square miles, is now under study. We hope to produce soon preliminary soils distribution maps, a tectonic map, drainage basin maps, and land use maps from this mosaic to demonstrate a few of the potential applications of space photography. Hopefully, with the launch of a long-life, multispectral, television satellite in proper orbit, we will soon be able to conduct similar studies on a national or worldwide basis. The two mosaics mentioned are or soon will be available from the Map Information Office of the U.S. Geological Survey.

Eventually we hope to add more sophisticated instruments, such as

- Metric mapping cameras with film-return capability use in topographic base mapping;
- color infrared cameras. This kind of photography is currently being studied to determine whether it can be used to recognize geochemical anomalies

related to ore deposits through recognition of relative vigor in plants. This is a difficult undertaking because there are many factors that affect plant vigor, including soil moisture or the lack of it, plant diseases and insect infestation, and merely root binding as plants reach maturity. It will probably be a long time before we can separate these factors to recognize only those features attributable to geochemical environment;

infrared scanners, which have been used in aircraft to record thermal variations on the earth's surface. We plan soon to install them in spacecraft to assess cooling or heating trends in volcanoes with the hope of predicting eruptions; to study hot springs and patches of hot ground such as that near Lordsburg, New Mexico, to assess potential geothermal power sources; to assist in recognizing and mapping certain rock types; and to assess the extent of near-surface coal mine fires;

radar imaging systems in aircraft, which have clearly demonstrated an all-weather mapping capability, as shown in a radar mosaic of Darien Province, Panama. The area covered about 10,000 square miles and closely approximates the view and detail that we hope to obtain by the proposed multispectral satellite. Radar imagery has demonstrated that fault systems (San Andreas) and surface texture related to topography and bedrock can be readily recognized. Certain rock types have been enhanced in some images of the Twin Buttes mining district, Arizona, where rhyodacite stands out on a cross-polarized radar image;

infrared spectrometers, which have been developed to determine gross rock types by their spectral response in certain wave lengths. Libraries of spectra of common rock types of known composition have been developed to serve as standards. The spectrometer, developed at Stanford University by Dr. R. J. P. Lyon, is now being tested in aircraft;

Passive microwave imaging radiometers, now under development, but at this time we have not clearly demonstrated applications to mineral resource problems.

Current and recent remote sensing activities in New Mexico include

Analysis of Gemini photography by Warren Hamilton of the U.S. Geological Survey, Denver office, who is studying the structural geology of the southwestern United States mosaic, and Roger B. Morrison, also of the Denver office, who is mapping soil patterns and distribution of the same mosaic in conjunction with color Gemini photography.

Analysis of Apollo—Saturn 6 color photography taken April 4, 1968, to be undertaken in conjunction with the above tasks.

Infrared investigations of the Lordsburg hot ground area, undertaken by S. J. Gawarecki and F. C. Canney of the U.S. Geological Survey in co-operation with W. K. Summers of the New Mexico Bureau of Mines and Mineral Resources.

Investigation of a strip of infrared imagery between Lordsburg and Silver City, New Mexico, completed by Walden P. Pratt of the U.S. Geological Survey, Denver office.

Infrared investigations relating to studies of missile impact craters at the White Sands Missile Range by H. J. Moore and others of the U.S. Geological Survey.

In summary, our geologists believe that color photography, color infrared photography, and infrared and radar imagery can provide new and useful information that will aid in the solution of diverse geological problems. Other types of data acquisition systems also offer hope and should be thoroughly investigated. The decision of whether to use aircraft or spacecraft data depends entirely on the scale of the problem to be studied. We are convinced that data from spacecraft can help us by providing synoptic views of large areas for regional studies of many types—and thereby enable the geoscientist to focus inward on targets to be studied in greater detail from aircraft or ground surveys. From space, we should also be able to study time-variant phenomena, such as early snow melt related to geothermal areas or ore deposits, shoreline processes, erosion, landslides, and volcanic eruptions by repetitive observation. Employment of remote sensor methods from parts of the spectrum beyond the visible, therefore, can add new perspective to our exploration techniques; coupled with space technology, we add a fourth dimension, that of TIME. The dimension of TIME becomes even more important as world population grows and places increasing demands on the providers of food, minerals, and other vital commodities.

Plan for Aiding Exploration and Development of New Mexico's Mineral Resources

by Alvin J. Thompson
New Mexico Institute of Mining and Technology

Mineral resources are a major factor contributing to the economic growth of New Mexico. The state's mineral production in 1967 had a value of 874 million dollars. Of this amount, mineral producers paid directly into the state and county treasuries in excess of 85 million dollars. Indirect revenues would add significantly to this total. These funds now provide a large share of the revenue derived for the support of the state's school and governmental activities.

Good business practice would dictate that a significant portion of the revenue received as a result of mineral production in New Mexico be reinvested to help ensure a continuing or accelerating high level of income from this source. Any proposed program or plan for economic growth of New Mexico should give due consideration as to what might be a proper level of state support for reserach and development activities in the mineral resources field so that the maximum benefit to the state and its people would be realized.

The State Bureau of Mines and Mineral Resources is by statute responsible for such studies and programs in the mineral industry field as will serve best to develop the state's mineral potential, as this in turn will best serve the interest of its people. However, the Bureau of Mines also is charged with a wide variety of service work which, under the appropriations normally provided, greatly limits other efforts that should be exerted to extend and improve the development and utilization of the state's mineral wealth.

The State Bureau of Mines with what funds are available has supported both long range and short term research in geology, mining, and metallurgy. Because of the large expenditures required, the state might not be justified in extensive exploration work. Nevertheless, the state can do things that would encourage others actively and extensively to explore for mineral deposits. The Bureau has endeavored to create interest in mineral development in New Mexico by the publication of geologic reports of potentially mineralized areas and of bulletins covering the known mineral resources of the counties which appear to offer the best prospects for future mineral development. Because of limited funds the coverage to date is far from complete. It is suggested that adequate funds should be provided to accomplish the following activities over the next five-year period.

The Bureau has published bulletins on the mineral resources of seven counties. A survey should be undertaken and reports issued on the remaining twenty-five.

Reports have been prepared on a number of mineral commodities but a great deal more such reports should be forthcoming. Of special interest, as seen in the light of present knowledge, are studies on uranium, silver, gold, rare earths, mica, strippable-coal, and building materials (including clays, silica, and sand and gravel).

Geology and ground-water reports have been completed for ten counties. There is an ever increasing need for such reports that cover the whole state. New studies should be expanded to include information on the geologic underground structure as it relates both to reservoirs and reserves of liquid fuels as well as water. Reports on the petroleum possibilities of each county would be of aid to petroleum exploration.

There have been tremendous advances in the art and science of geophysical prospecting in recent years. Important finds being made with the aid of geophysical methods attest to the increasing effectiveness of the methods. It is proposed that the state support geophysical surveys of the areas in the state that appear to offer the most promise of having subsurface mineral emplacements. The program should comprise airborne electromagnetic, gravity, magnetic, and radiometric surveys. In some cases geochemical ground surveys should be made to supplement the records. It is suggested that the initial work be in areas where the bulk of the land is owned by the state, since the greatest financial gain to the state would be forthcoming from new discoveries made on these lands.

These studies of the water and mineral resources of the counties and of commodities available in the state as a whole, together with the geophysical surveys, would help to satisfy existing demand for mineral information. By providing an account of the quality and extent of known and estimated mineral occurrences in the various areas of New Mexico, and by providing scientific and geologic guides to potentially new deposits, these studies would be a great stimulant to further mineral development in this state.

It is anticipated that to complete this program of field studies in the course of a five-year period would require an expenditure in the order of $500,000 a year. This is an amount equal to only about 0.06 percent of the value of the state's annual mineral production. It seems reasonable to believe that appropriations so provided would yield returns far out of proportion to the amount invested.

A relatively short period is proposed for studies to reveal the nature and extent of the state's mineral wealth because much is to be gained by having such information available soon. Because markets are often a determining factor in the exploitation of some commodities, mineral developments in one area often preclude or delay developments in adjoining areas. This is a consideration that can apply on a statewide basis. New Mexico in the past has lost markets which it might have had, both within and without the state, because other areas have been ahead of it in the development of supplies to meet commodity demands as they occur.

The proposed five-year program should be initiated to make a survey of the commodity resources of New Mexico and complete geologic county reports on mineral and water resources. An annual appropriation of $500,000 a year is suggested.

The other phases of state-financed activities in support of mineral development in New Mexico should be on a continued basis, as part of the normal work now being performed by the New Mexico Bureau of Mines and Mineral Resources. The purely informational and service activities would require an expenditure of about $300,000 annually. It is believed that the augmentation of Bureau appropriations to a level in the order of $1,000,000 a year to incorporate activities in all the phases is more than justified. For the five years during which the surveys were being conducted, the total appropriations for the Bureau would be about $1,500,000 annually.

To aid in the proper expenditure of such funds it is recommended that an advisory council composed of representatives of the mineral industries and the state government be appointed by the governor. This council would review and approve all programs proposed by the Bureau and consider any other programs or areas of activity that may be suggested to it. Such a council should serve the purpose of ensuring maximum economy and effectiveness in carrying out this state-supported work.

In conclusion, it should be pointed out that the state has a special interest in its mineral resources. One sixth of the mineral lands in New Mexico is owned by the state. By virtue of this ownership, the state receives about $35,000,000 each year in revenue in the form of bonuses, royalties, and rentals from those who lease the state-owned lands. A few percent increase in revenue from this source alone would more than justify the expenditures proposed in this report.

Value of Mineral Resources to New Mexico

by W. Wilson Cliff

(from Albuquerque Journal, Oct. 23-26, 1967)

(What is the extent of New Mexico's mineral wealth, what is its future? What is its possible role in the industrialization of the state? What is its contribution to state and local government? What changes in public policy would make New Mexico's mineral resources more valuable to the state?)

CORONADO WAS FIRST

Rumors of vast mineral wealth brought the first exploratory expedition, that under the command of Francisco Vasquez de Coronado, into what is now New Mexico more than 400 years ago.

That venture ended in failure and disgrace two years after it began in 1540.

But in the centuries that have followed, the wealth sought by Coronado has proved itself a reality. Prior to Jan. 1, 1967, the mines, quarries, open pits, and deep wells of New Mexico had yielded an estimated $11.5 billion in new wealth. With the aid of new technology and the upsurge of new values and scarcities, $10.6 billion or 92 percent of the all-time total has been extracted from the earth in the last 26 years.

Today, New Mexico is a giant among the 50 states in its production of mineral wealth. In 1962, it ranked seventh among the 50 states in its annual production and first among the states of the Rocky Mountain region.

Today, New Mexico stands first among the states in its production of uranium, potassium salts, and perlite. In the last year it has moved from sixth to fifth place among the states in the value of its production of raw petroleum—crude oil. natural gas, and natural gas liquids. It ranks fourth among the copper-producing states.

Annual mineral production in New Mexico is rapidly approaching the $1 billion level. Total value of its production—including crude oil, natural gas, helium, sand, gravel, clay and limestone—last year was estimated at $863 million.

URANIUM PRODUCTION INCREASES

Uranium, one of the state's newest and more glamorous mineral products, has been produced commercially in New Mexico only since 1950. Yet the New Mexico Bureau of Mines and Mineral Resources predicts that the cumulative value of uranium produced in the state will pass the $1 billion mark before the end of this year.

But uranium, as yet, is not even among the "Big Three" of New Mexico's mineral products. The "Big Three" last year were crude petroleum, the year's production of which was valued at $352,101,000; potassium salts, $118,262,000 a year (1965), and natural gas, $117,263,000 a year.

Last year the state's petroleum production was valued at $520,934,000, equivalent to 63.7 percent of New Mexico's total mineral production in 1965. At this rate, the state's petroleum industry rings up more than $1 billion in less than two years.

Other major contributors to the state's annual production total are copper, $79,724,938; uranium concentrate, $73,463,593 (1965); coal, $9,131,835; sand, gravel and related products, $14,912,071; zinc, $4,150,005; perlite, $ 2,676,55 7; helium, $ 2,905,000 (1965); and stone, $4,878,000 (1965).

MOLYBDENUM CONTRIBUTES $10 MILLION

Output of the state's major molybdenum mine at Que st a , production data from which is classified and confidential, was estimated to have approached or exceeded $10,000,000 last year, its first full year of production.

Impressive as these figures may be, they represent only a portion of the contribution of mineral production to the general economy of New Mexico.

The Bureau of Business Research of the University of New Mexico stated in a 1965 study that "in the matter of production value, New Mexico's most important economic activity is mining. Such extractive industries as potash, copper, uranium, and oil and gas are notably important in this state."

In the same study, basing its calculations on 1960 production figures, the bureau credited New Mexico's mining industries with 10.6 percent of the total gross output of the state's major industry groups.

The bureau estimated that payrolls in New Mexico mining and closely allied milling activities last year totaled $124.2 million or 6.4 percent of the state's estimated total employment income of $1.9398 billion. Mining and related milling activities provided employment for 16,700 persons—approximately 4.7 percent of the state's total work force.

Mining enterprises also contribute a substantial share of the costs of maintaining public schools and paying the costs of state and local government. Again using 1960 figures, the Bureau of Business Research estimated that mining industries contributed $62.3 million to state and local governments—between 7.3 and 8.3 percent of the industries' gross output.

INDUSTRY TAXES PLAY IMPORTANT ROLE

The 1960 tax figures have been subject to abrupt upward revision, both dollarwise and percentagewise, in all the years that have followed. In the fiscal year ended June 30, the petroleum industry alone contributed more than $ 73 million to state and local governments in New Mexico—over and above corporate and individual income taxes paid by petroleum operators.

In its preview report on its exhaustive input-output study—an effort to evaluate the impact of each segment of the state's economy on every other sector—the Bureau of Business Research evaluated the impact of each dollar generated by the uranium industry as 37 cents on other sectors of the state's economy. The over-all economic effect of a dollar in oil-and-gas field services was rated at 31.62 cents; copper, 20.24 cents; potash, 19.64 cents; other mining activities, 17.63 cents; and petroleum and natural gas, 17.31 cents.

MINERAL RESOURCES PRODUCTION GROWS

New Mexico's production of mineral resources last year, estimated at $863 million, is impressive, but events of the last two years provide strong indication that it may be merely a beginning.

Two copper mines now being rehabilitated in Grant County promise to boost the state's copper production by 1970 to 177,000 tons annually-77 percent more than the state's total copper production last year.

Commitments and timetables of the state's two largest coal mines, the York Canyon Mine in Colfax County and the giant Navajo strip mine in San Juan County, point to peak production of 10,770,000 tons of coal annually by the two mines in the early 1970's—more than three times the state's total coal production last year.

AEC CHANGES POSITION

A shift in policy last year by the Atomic Energy Commission opened the door to sales of uranium oxide to certain licensed private enterprises. This set off a series of contracts from the nation's major electric utilities for the construction of nuclear-powered generators. In turn, utilities and reactor manufacturers contracted with New Mexico's major uranium producers for future supplies of uranium. It has been estimated that these contracts will result in production of an additional $200 million worth of uranium in the next seven years.

Meanwhile, exploration for uranium over the entire northern half of New Mexico—an activity which virtually came to a standstill late in 1957—has been resumed with new vigor.

In mid-1966 the Federal Power Commission authorized El Paso Natural Gas Company and Transwestern Pipeline Company to deliver an additional 600 million cubic feet of natural gas daily to the southern California market. Virtually all this added production will come from New Mexico's San Juan Basin and the Permian Basin of southeastern New Mexico and west Texas. Little, if any, of this added market was reflected in New Mexico's 1966 production figures.

POTASH INDUSTRY CURTAILS PRODUCTION

Developments in the potash industry have taken a reverse turn, and the future of New Mexico's potash production is the largest question mark in today's mining outlook.

Production of 2,862,000 tons of potassium salts in the Carlsbad—Hobbs area in 1965 and an even greater tonnage last year accounted for nearly 90 percent of the nation's potash production and almost 20 percent of world production.

But development of a larger, richer, and deeper potash deposit in Saskatchewan—in part by the same producers who pioneered the development of New Mexico's potash beds—has changed the world and domestic market outlook for potash.

Within the last 10 days, the pioneer New Mexico producer, U.S. Borax and Chemical Corporation, announced that it will close down its New Mexico operations on November 1 0—ten months in advance of its earlier announced schedule. The decision will affect 850 employes in mines, refinery, and offices. Another potash company recently reduced its operations in New Mexico 50 percent by laying off almost 400 employees.

CANADA IN COMPETITIVE POSITION

By 1970 Canadian mines and mills now operating or under construction are expected to be producing almost two and one half times what the New Mexico operations are now producing. The resulting competitive situation is expected to reduce the market for New Mexico potash to a three-state area.

Potash today is still a vigorous industry in southeastern New Mexico. Hope for the future rests largely on the belief that some other major producer will take over the U.S. Borax facilities and mining claims.

New hope for New Mexico potash also rises from the increased demand for chemical-grade potash, for in this respect Carlsbad potash has a quality advantage over the competitive Canadian product. Chemical-grade potash is in increasing demand from producers of quality toilet soaps and shampoos, optical glass, enamel ware, pigments, medicines, cosmetics, explosives, fireworks, matches, insecticides, and even chocolate.

New Mexico also has vast stores of other mineral resources—virtually untapped to date—waiting for the right combination of prices, process, demand, transportation rates, technological changes, and world wide geography and politics.

MINERAL PRODUCTION IS JUST STARTING

Dr. Frank E. Kottlowski, acting director of the New Mexico Bureau of Mines and Mineral Resources, estimates that the White Sands area, exclusive of the White Sands National Monument, offers pure white gypsum in sufficient quantity to supply the nation's needs, at the current rate of usage, for at least 200 years. White Sands is but one of the state's vast gypsum deposits. Yet last year this state produced only 145,745 tons of the product—mostly for the two small plants in the Albuquerque—Santa Fe area.

New Mexico offers one of the nation's major sources of manganese and, indeed, during and shortly after World War II the state responded generously to the nation's defense requiremnts. In normal times India offers a larger, higher grade, and lower cost supply.

TAOS COUNTY LEADING PERLITE PRODUCER

Most of the state's production of perlite, "the popcorn mineral," was centered in Socorro County, but today the vast sources in north-central New Mexico are beginning to be tapped. Steadily the market for this product, used as a bonding agent for concrete and plaster, is growing. Renewed emphasis on high-rise buildings and the resultant requirement for large supplies of light weight aggregate may be expected to open new markets for this product.

Perlite also is believed to have a bright future in the agricultural market, as yet undeveloped. Limited applications have proved perlite's quality as a soil conditioner, loosening and lightening tight soils, and increasing the water-retention capacity of porous and sandy soils.

The market for molybdenum, an element essential to the growing aerospace industry because of its inherent hardness and resistance to heat, is expected to expand steadily in the years ahead.

Markets for the state's vast stores of sand, gravel, stone, and other quarry products are expected to increase steadily but—because of transportation costs and low per-pound market prices—only so fast as the state's population and construction industry expands, for economy and the general nature of such products dictate that they must be used within relatively short distances from their point of origin.

HOW LONG WILL THE SUPPLY LAST?

Evidence of increasing production and expanding markets for New Mexico's vast mineral resources inevitably gives rise to one salient question:

How long will the supply last?

And the answer, in the most elaborate form it can take, leaves much of the question unanswered.

To date, elaborate geological studies cover only seven of New Mexico's 32 counties, about one fifth of the state's total area. The mineral wealth underlying the remaining four fifths of the state is unknown and, at best, only inferred.

From the facts already known, the outlook for the future is both bright and bleak, depending on the particular mineral resource which may claim one's interest.

ADDITIONAL URANIUM RESERVES SOUGHT

The surging new demand for the state's uranium production presents what appears to be a crisis, yet the uranium industry itself, the Atomic Energy Commission, and even the growing number of large electric utilities committing millions to new nuclear generators refuse to be disturbed.

Earlier this year, the Bureau of Business Research of the University of New Mexico published this statement:

> Our (U.S.) reserves of (uranium oxide), however, have dwindled rapidly—from a peak of 241,000 tons at the end of 1959 down to 145,000 early last year, with 42,500 (tons) already contracted for by the AEC. Expressed as ore, our reserves last May were down to 32 million tons 'measured, indicated, and inferred.'
>
> Of this total, New Mexico possessed 22.7 million tons (77 per cent of the total). Press reports in October put proved U.S. reserves then at 61 million tons, with New Mexico possessing about 29 million, or 48 percent. In the 1960-66 period alone we mined 19.4 million tons. At that rate (and all indications are for a greater rate), by 1970 we would have depleted even our 'inferred' reserves of today.

MORE NUCLEAR POWER

Reassurances by Dr. Glenn T. Seaborg, chairman of the Atomic Energy Commission, provided the basis for decisions by many major electric utilities to build nuclear power plants. Among other things, Dr. Seaborg predicted that renewed exploration, with rising demand as the chief incentive, would uncover ample uranium reserves.

Last November, Dean A. McGee, chairman of the board of Kerr-McGee Corporation, echoed Dr. Seaborg's reassuring analysis:

> During the peak years of 1956 and 1957, about 9 million feet of (exploratory core-drilling) hole was drilled each year. Exploration drilling will soon equal or *exceed* this level if the uranium industry can foresee a market for uranium at prices commensurate with the high risks taken.
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> The growth of reserves, which in the past has generally been proportional to the size of the discovery effort, should respond very favorably to the fact that the current exploration program is being built on the base of greater knowledge of uranium geology, improved exploration methods and tools, and experienced personnel.

Both McGee and Dr. Seaborg referred confidently to the fact that between the early part of 1952 and the end of

1956, AEC-encouraged exploration uncovered an average of 37,300 tons of uranium oxide a year—about 1.3 times the projected domestic requirement for uranium in 1980. The AEC terminated its offer of a market for uranium ore discovered after Nov. 24, 1958, and exploration virtually ceased.

PETROLEUM DEPLETION WORRIES SOME

In the light of known reserves, the outlook for petroleum production in New Mexico in future years also is discouraging in some respects.

For example, according to figures published by the Independent Petroleum Assn. of America, new reserves of natural gas discovered in New Mexico last year totaled only 375.7 billion cubic feet, while production totaled 887.2 billion cubic feet, reducing the state's reserves by 511.5 billion cubic feet.

This depletion of a known reserve, however, came at a time when petroleum exploration, coupled to market conditions, was virtually at a standstill in New Mexico. Last year only 1258 new oil and gas wells were drilled in this state as compared with an all-time total of 33,446 wells. Only 258 of last year's wells—about 20 per cent of the total—were exploratory wells.

The blow also is softened by the fact that natural gas reserves discovered prior to Jan. 1 this year totaled 27.4 trillion cubic feet, while all-time production in the state totaled 12.7 trillion cubic feet, leaving a proved reserve of 14.7 trillion feet.

The petroleum outlook is brightened somewhat by the fact that new reserves discovered in the state last year more than doubled the state's production of crude oil during the year and exceeded by half the year's production of natural gas liquids.

DISCOVERIES INCREASE

Last year, new discoveries turned up 246,126,000 barrels of crude oil as compared with the state's production of 116,724,000 barrels, leaving a proved reserve of 2,205,258,000 barrels—almost double the state's all-time production of crude. Discoveries in 1966 also turned up 54,005,000 barrels of natural gas liquids against the year's production of 37,053,000 barrels, leaving proved reserves of 559,783,000 barrels—nearly twice the state's all-time production.

The outlook for the state's other major mineral resources—copper, potash, and coal—is excellent. The most recent estimates are found in a 437-page *book, Mineral and Water Resources of New Mexico,* prepared by the United States Geological Survey at the request of U.S. Senator Clinton P. Anderson, D-NM, and published by the New Mexico Bureau of Mines and Mineral Resources in 1965.

COAL RESERVE 62 BILLION TONS

Dr. Frank E. Kottlowski, acting director of the State Bureau of Mines, and Edward C. Beaumont of Albuquerque, who jointly prepared the section on New Mexico coal, report:

> The coal resources of New Mexico are estimated at about 62 billion tons, of which 50.8 billion tons are subbituminous (1000 times the state's projected coal production in the early 1970's and more than 3000 times the state's total coal production last year) and 6 million tons are anthracite.

Writing about the state's copper resources in the same publication, W. R. Jones of the U.S. Geological Survey, Denver, had this to say about reserves:

> Although few mine reserve data are available for copper, a rough estimate is possible on the basis of past production and geologic inference. It is estimated that known, partly developed and possible reserves, to say nothing of undiscovered yet statistically likely resources, of copper in New Mexico are about three times what has been produced to date (2.5 million tons). Most of the reserves for the next decade or two are in Grant County.

80 PERCENT OF POTASH REMAINS

U.S. Geological Survey geologists B. R. Alto, R. S. Fulton, and L. B. Haigler, who contributed the section on potash, had this to say about reserves:

> A recent canvass of southeastern New Mexico potash producers regarding presently mineable reserves held under lease, together with data compiled by the Geological Survey regarding unleased reserves, indicated a crude sylvite ore tonnage reserve of approximately 1.3 billion tons with an average (potassium oxide) grade of approximately 17 per cent.
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> The crude langbeinite ore tonnage reserves are about 0.2 billion ton with an average (potassium oxide) grade of approximately 9 percent. The indicated reserves are present in beds containing not less than 15 percent (potassium oxide) sylvite, 8 percent (potassium oxide) as langbeinite, and in beds of no less than 4 feet thick.

U.S. Geological Survey surveys indicate that New Mexico production of crude potash ores in 1963 totaled 16.4 million tons, and total cumulative production of crude potash ores in the state since initial production in 1931 was 202.6 million tons—less than 20 percent of the remaining mineable reserves.

It is more a matter of mining economy than of human nature that extractors will remove the easy-to-reach and high-grade resources from a known reserve before going after the deeper and the lower grade ores.

Officials of Kennecott Copper Corporation acknowledge frankly that they are now—in the face of a favorable price structure and a good world market—mining and processing ores that they could not afford to utilize a few years ago.

TAX INCENTIVE AIDS PRODUCER

The UNM Bureau of Business Research, in its March 1967 issue, attributed the decision of U.S. Borax and Chemical Corporation to abandon its New Mexico operations and move to Canada to the fact that it had depleted its higher grade ores. Said the bureau: "The fact that the pioneer company has just about mined out its best ore and would have to install a totally new multimillion-dollar refinery to handle remaining ores seems the basic reason for the move to Canada."

A mineral industry survey released by the U.S. Bureau of Mines on July 10 of this year also implied the depletion of higher grade potash ores with this statement: "The calculated average grade of crude potassium salts mined in New Mexico (in 1966) dropped to 17.55 percent (potassium oxide) compared with 18.12 in 1965."

When a mine operator passes over a low-grade or costlyto-reach ore deposit, he does so with the hope that the future market—a combination of price and demand—or future technology will ultimately provide a means whereby he can develop the bypassed source economically.

In the history of mining, such- a hope has frequently been vindicated.

OIL RECOVERED BY SEVERAL METHODS

The petroleum industry, by its physical nature, dictates that the easier-to-reach resources will be the first to be produced. With little regard for the economics, the operator has little choice. First he produces and markets the crude oil and liquids brought to the surface by the tremendous pressure of underground gases. In fact, he literally fights these enormous pressures with shut-in devices to hold his production down to the limits of his market and storage capacity.

As the underground pressure is dissipated, he will install a pump. As production declines even further, he will rework his well or, ultimately, resort to one of several secondary recovery methods—water flooding, gas injection or thermal pressure—to produce the last commercial drop of oil.

NEW EXPLORATION TOOLS AVAILABLE

In the opening chapter of *Mineral and Water Resources of New Mexico,* U.S. Geological Survey geologist George O. Bachman of Denver said:

> Although the state was prospected extensively during the late 19th and early 20th centuries, new tools that are now available to the modem prospector have essentially reopened the field to further work that could lead to major new discoveries. The science of geophysics with its newly developed instruments for use in the air and on the ground has become much more sophisticated and highly specialized.
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> Geochemical prospecting is a rapidly developing and practical field technique for the detection of small, but anomalous, amounts of metals in soil, water, and plants. Isotope chemistry and physics, X-ray and spectroscopic analysis, highly sensitive chemical techniques and other refined laboratory methods make possible the more accurate identification and quantitative determination of trace amounts of elements that may give clues to the location of undiscovered ore deposits.
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> The future of mineral resources production is dependent on continuing demand, discovery, exploration, and development. As indicated in numerous chapters in this report, development of many of New Mexico's resources is increasing . . . .

NEW MEXICO IS SIMILAR TO COLONY

Today New Mexico—one of the wealthiest states in the nation on the basis of her natural resources—finds herself in a role not unlike that of a nineteenth century colony, groveling in her own poverty while pouring out vast stores of raw materials for the enrichment of an industrialized motherland.

The state's gross mineral product, now exceeding $800 million a year, reaches the ultimate consumers with a composite price tag that can be expressed only in billions of dollars. Much of the difference between the millions and billions represents payrolls and corporate profits going to the citizens of other states.

Not so many years ago the state desperately sought developers and marketers of her untapped natural resources. Among the economic highlights in her recent history were the purchase of the old Maxwell Land Grant by Kaiser Steel Corporation—a development which meant a renewed market for the vast coal reserves in Colfax County; the completion of two crude oil pipelines from New Mexico's Four Corners, one to California and one to the Gulf Coast of Texas—developments that meant, at last, a market for a rapid succession of oil discoveries in the San Juan Basin; and completion of the big Arizona Public Service Co. power plant near Farmington—a development that meant a market for the untapped coal reserves on the Navajo Reservation.

SECOND LOOK NEEDED

Today many of the state's officials, legislators, economists, and industrial leaders are taking a second look at

New Mexico's lack of processing industries and asking themselves a salient question: Need we content ourselves with half a loaf?

The Bureau of Business Research of the University of New Mexico, in its 1965 preview to its input-output study, observed that "the economic impact of mining is mitigated by the fact that most of its production is (1) processed or refined in other states or (2) sold to the federal government. For these industries, the ratios of exports to total gross output (sales) are these: Copper-98.3 per cent; petroleum and natural gas-93 per cent, and potash-95.8 per cent."

R. F. Montgomery of Hobbs, in his contribution to the volume *Mineral and Water Resources of New Mexico,* offered this comment about the state's oil and gas resources:

> Although New Mexico produces far in excess of its own requirements for oil, most of the crude oil is transported from the state for refining, and finished products (are) returned. New Mexico, far richer than most states in energy resources, has not yet successfully built the manufacturing industries that utilize inexpensive energy or industries that utilize hydrocarbons as raw materials . . .
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> The paucity of processing plants for the utilization of these vast volumes of energy and raw materials within New Mexico has resulted from many factors. These include an excellent export system, federal regulatory practices which do not encourage local utilization of natural gas, and probably a lack of appreciation of the marketing opportunities that New Mexico offers today compared to 38 years ago when the pattern for many of these factors was being set.

SOME N.M. PRODUCTS READY FOR CONSUMER

Actually, export figures present an incomplete picture of the processing that does go on in New Mexico, for many segments of the state's mineral industry turn out their products packaged and ready for the consumer.

For example, most of the state's natural gas production leaves New Mexico consumer-ready after being subjected to an elaborate "washing" process and treatment at plants near the source.

Practically all the copper ore mined in New Mexico goes to market as almost-pure metallic copper after milling and refining at Kennecott's Chino mill in Hurley. However, Phelps Dodge Corporation, now rehabilitating its old mine at Tyrone, and American Smelting, Refining and Mining Company, preparing to open its mine at Fierro, have indicated they will concentrate their New Mexico ores at the source, but the concentrates will be moved to the two companies' smelters in nearby Texas and Arizona—at least in the early stages of their renewed mining operations.

URANIUM MADE INTO "YELLOWCAKE"

New Mexico's uranium ores are milled near the mine sites, and a substance called "yellowcake"—dominantly uranium oxide but frequently with some impurities—is extracted. "Yellowcake" is uranium in a marketable form, but it is not the end product. It must pass through a half-dozen additional processes before it is ready for use in a nuclear reactor. One of those processes, under present law, must be performed by the Atomic Energy Commission in one of three plants—one located at Paducah, Ky., one at Oak Ridge, Tenn., and the other at Richland, Wash. The recent decision of Kerr-McGee Corporation, one of the principal miners and millers of New Mexico uranium ore, to locate its sophisticated uranium hexafluoride plant in Oklahoma was considered a harsh blow to New Mexico's industrial development along lines closely related to its native resources. To New Mexicans, it seemed logical that such a plant be situated close to the company's and the nation's major source of raw materials.

POTASH PROCESSING ADDS $60 MILLION

New Mexico potash is refined and, in most instances, ready for the ultimate consumer when it leaves the state. An idea as to the value added to the crude potash ores by refining is implied in the disparity of value figures on 1965 production published by two public agencies.

The state mine inspector's office, evaluating potash ores in their crude state, valued the year's output at $57,556,916. The U.S. Bureau of Mines, evaluating the finished product, potassium salts, published a figure of $118,262,000. The value added by processing would appear to exceed $60 million.

Molybdenum ore, a relatively new product of New Mexico and one of growing importance, is partially processed in the state. Molybdenum Corporation of America runs the ores from its new mine near Questa through its nearby mill to produce a concentrate with a molybdenum content of about 45 percent. The concentrate is then shipped by truck and rail to Pennsylvania for further processing in a company refinery which has been in use for a number of years. The refinery processes concentrates from a number of other mines and mills.

NEW MEXICO NEEDS REFINERY CAPACITY

Statistics concerning the state's No. 1 mineral product, crude oil, emphasizes both the need and the opportunity for an industrial development centered around a major raw product.

New Mexico processes a smaller percentage of its own crude oil than any other major oil-producing state.

Figures presented to the 1967 New Mexico Legislature showed that only 34,475 barrels of crude oil daily—slightly more than 10 percent of the average daily crude oil production of 340,100 barrels a day—is processed in New Mexico refineries.

Texas, the nation's No. 1 oil producer, processes 94 percent of its own product. Louisiana, now No. 2, processes 53 percent of its products in Louisiana-based refineries. California, No. 3, processes 60 percent more than its own crude product. Oklahoma, No. 4, processes 74 percent; Wyoming, 33 percent; Kansas, 117 percent; Mississippi, 82 percent; and Colorado, 46 percent.

What happens to New Mexico crude not refined in the state?

Dr. Frank E. Kottlowski reports that approximately 119 million barrels of crude were produced in New Mexico in 1965. Of this total, 11.5 million barrels were processed in the state. The remainder went out of the state by pipeline. Texas refineries processed 40 million barrels of the total; 60 million barrels went to Midwestern refineries, and 7 million barrels were processed in California.

LACK OF REFINING HURTS STATE

But this is what hurts, economically: New Mexico refineries, running at total capacity, are capable of turning out only 59 percent of the refined products required by the state. The remainder comes back into the state, much of it through product pipelines from Amarillo and El Paso, the remainder by truck from other Texas refineries.

Walter Famariss, operator of a refinery in Hobbs with a daily capacity of 4500 barrels of crude, estimates that he can add $1 to the value of every barrel of crude that passes through his refinery. That dollar represents wages paid to New Mexicans, taxes, other materials used in the refining process, overhead and company profits. Famariss terms his $1 estimate "a ball park figure," pointing out that the petroleum industry itself has used a figure as high as $1.25.

But taking Famariss "ball park figure" as a basis, one could conclude, from figures available, that New Mexico's five small refineries, with a combined capacity to handle 35,600 to 36,100 barrels of crude daily, could add more than 12.5 million dollars annually to the economic value of the crude they can process. It means that New Mexicans could add another $8.9 million to the state's gross annual product if New Mexico refineries only processed all the refined products consumed in the state. It means the state's gross annual product could be increased by $107.5 million if all the crude oil produced in the state were refined here.

NEW MEXICO OFFERS GOOD MARKET

But Famariss doesn't stop with his discussion of the state's crude oil potential.

"New Mexico, as one of the nation's wealthiest states in raw materials, must be made cognizant of its poor economic position," said Famariss. "What is happening to our crude oil is happening to our other resources—even our water.

"New Mexico offers a tremendous market for fertilizer," said Famariss. "I'm not referring to potash. Our soils don't need a great deal of that. I'm talking of ammonium nitrate, and we buy a lot of it here. The principal raw material going into ammonium nitrate is natural gas. Yet our natural gas is going outside the state, and not one unit of ammonium nitrate is produced within the state. There are plants all around New Mexico—at its borders—in Texas."

New Mexico coal presents still another picture: Most of the coal produced in the state last year—that produced in the Navajo strip mines in San Juan County—was actually consumed in the state near the point of production. It was burned to produce electrical power—for delivery in Arizona.

COAL PLAYS IMPORTANT ROLE

But ultimately some of the power generated by that Navajo coal will be used for the benefit of New Mexico. Construction was started last year on two new units of the Four Corners power complex. One of the six western utility firms building the two units and planning to share in their output is Public Service Company of New Mexico.

Coal produced at the new push-button mine and mill at York Canyon in Colfax County is transported 1100 miles by unit train to southern California for conversion into coke and a variety of valuable by-products.

Distinctive to New Mexico's newly revived coal industry is the minor economic impact of the state's space-age production on the state itself.

There was a day in New Mexico when the production of 3 million tons of coal meant jobs—thousands of jobs. Today coal mining goes forward with only a handful of persons aware of the fact that coal is being mined.

MORE COAL PRODUCED WITH LESS MEN

Last year 287 coal mine employes-100 working underground and 187 on thy surface—turned out 2,933,757 tons of coal valued at $9,131,835.

Back in the days when coal was "Mr. Big" among New Mexico's mineral industries, mining that much coal meant employment for almost 4500 persons.

In 1913, when 262 miners and two rescue workers were killed in a single mine diaster at Dawson, 4466 miners were employed by the state's coal industry, and the net production was 2,594,198 tons of coal. In 1931, when the state's coal output had dwindled to 1,613,414 tons, 2736 persons were still employed by the industry. By 1938, employment in coal mining had slipped to 2345, and the yield was 1,239,716 tons.

Today behemoth machines in the Navajo strip mines and sophisticated and automated mining equipment in York Canyon make New Mexico coal production virtually a painless—and a manless—operation.

New Mexico leans heavily on its mineral industries as a source of revenues.

Each year these extractive industries pay to the state and its taxing subdivisions a sum—in taxes, rents, royalties and bonuses—equal to almost half of the state's annual general fund and public school appropriation.

During the fiscal year ended June 30, 1967, the state's oil and gas producers paid $73,135,572 to the state, local governments, and state institutions. Taxes, rentals, and royalties paid by other mineral industries, as predicted on 1966 valuation, production and sales figures, generated a sum ranging between $9.3 and $10.3 million.

These figures do not include $972,844 paid last year by a handful of small petroleum processors in the form of manufacturers' privilege tax. Neither do they include the corporate and personal income taxes paid by firms and individuals producing the petroleum and solid minerals. Nor do they include income, property, or sales tax paid by those employed in the extraction and processing of the state's mineral wealth.

TAX STRUCTURE NEEDS OVERHAUL

But an examination of the tax structure as it applies to the extractors and processors of mineral resources points clearly to these conclusions:

—The tax structure is a patchwork creation—added upon, stacked up and diminished according to the expediency of a given moment.

—This structure is highly discriminatory against one segment of the mineral industry as opposed to another.

—Uses of revenues generated by this tax structure discriminate against future generations who, theoretically, will be deprived of the mineral wealth produced today.

—Some of the taxes imposed by the state operate in such a way as to discourage the development of vigorous New Mexico processing industries.

The mineral industries pay more and higher taxes to the state than other enterprises. The theory, almost universally applied by American states, is sound:

The state's subterranean wealth rightfully belongs to the state and its people. Those who extract, and permanently diminish, that wealth in hope of turning a profit should compensate the people through taxes.

INDUSTRY TAXED, RETAXED, AND TAXED AGAIN

Consequently, actual production is the prime basis for taxation, and production—itself subject to wide fluctuation—is taxed, retaxed, and taxed again.

A corporation producing oil or solid minerals on state-owned land will pay the state an annual rental fee for use of the land. If its quest is successful it also will pay the state a royalty for every barrel of oil, unit of natural gas, or pound of ore extracted.

If the lease is on federal land or Indian land, the producer pays the owner in the same way, although the rates may differ. A portion of his federal lease and royalty payments is returned by the federal government to the state.

Then the state tax structure takes effect.

First the producer pays a severance tax—a prescribed percentage of the market value of the mineral removed at the point of extraction to the state bureau of revenue.

Then he pays an extraction and processing tax on the same production. This tax actually is predicated on sales and is intended to correspond with the gross receipts or sales tax imposed on mercantile industries. This tax also is collected by the bureau of revenue.

If his product happens to be potash, he pays an added 3 percent potash mining tax on certain production. In 1955, $77,711.32 in potash sales were subject to this tax. In 1966, sales subject to this tax totaled $119,764.72.

Then the state Tax Commission takes over and sets up the dollar basis for ad valorem taxation. The Tax Commission appraises the land and improvements owned by the producer and used to extract mineral wealth—mines, equipment and installations; oil wells and equipment; pipelines; storage tanks; power units. Then the Tax Commission takes the producer's production figures—once more. These figures are certified to the county assessors in the 32 counties, and mill levies are applied to both improvements and production according to the locale of each.

TAXES ARE NOT UNIFORM

Assessments applied by the Tax Commission are not subject to further reduction by the county assessor. They go on the assessment rolls as certified.

In 1965 the Tax Commission assessed mining properties, subject to ad valorem taxes, at $85,397,995, and in 1966 the total was $102,272,170. Production in 1965 subject to ad valorem taxation was valued at $89,181,956, and in 1966 it was valued at $88,267,311. These totals exclude figures applied to the petroleum industry.

All taxes imposed on the petroleum industry in New Mexico, even local and state ad valorem taxes and state royalties, are collected and audited by the State Oil and Gas Accounting Commission. However, the State Tax Commission still furnishes the property valuations on which the ad valorem taxes are based.

VARY GREATLY BETWEEN MINERALS

The severance tax rate applied to the minerals which have been in production in New Mexico over a long period of years is low—one eighth of one percent of the market price. This rate applied to such products as coal, pumice, sand and gravel, mica, perlite, manganese, molybdenum, gold, silver, lead, zinc, vanadium, beryl, salt stone, scoria, gypsum, and iron.

But the rate applied to copper, also one of New Mexico's older mineral products, is one half of one percent.

And rates applied to the mineral products relatively new to the New Mexico scene are still higher. The rate on petroleum and potash is two and one half percent. The rate on uranium, actually the last to join New Mexico's family of major mineral products, is only one percent.

Timber, a nonmineral, also is taxed at one eighth of one percent—but with no deductions.

The inequity in rates is compounded when the natural resource extraction and processesing tax is applied. For most minerals the rate is three quarters of one percent. Then three percent is added for certain potash sales. The rate applied for the preparing of timber for commercial use is three eighths of one percent.

NET PROCEEDS TAXED

Inequities are compounded still further in exemptions that tend to make these taxes net proceeds rather than gross proceeds taxes.

Deductible in most instances are state and federal royalties—but not Indian royalties—paid on production. Costs of loading, hoisting, and crushing minerals are deductible in most instances, and costs of transporting them to a beneficiating plant are applied to some.

Transportation to the point of first sale are deductible for some minerals, not for others.

When the tax rate is applied for natural resource extraction and processing, a deduction is allowed for "sales of coal in carload lots" which virtually eliminates the tax on all coal mined in New Mexico. Another deduction is applied on sales or transportation in interstate commerce.

AMOUNT OF TAXES PAID

Here are the sums the state's severance tax on the various segments of the mineral industry produced in 1966:

Potash, $ 494,619.98 ; uranium, $ 248,191.51 ; copper, $241,481.41; coal, $7523.27; timber, $912.48; pumice, $37.45; sand and gravel, $2434.79; perlite, $2116.95; manganese, $534.89; molybdenum, $8334.90; gold, $228.41; silver, $115.68; lead, $280.24; zinc, $2831.26; vanadium, 59 cents; stone, $804.94; scoria, $151.44; gypsum, $422.65; and others, $601.59. Petroleum paid $11.1 million.

Guidelines employed by the State Tax Commission for evaluating mining properties are, admittedly, unrealistic. For example, the assessment rate for a mile of 31-inch trunk pipeline is set at $16,800. The figure on a 50,000-barrel oil storage tank is $10,000; that on a 51,000-barrel tank is $7650. The rate applied to a 22,500-foot oil well—deeper than any ever drilled in New Mexico—is $11,500 for its first year after completion, as low as $10,300 in subsequent years.

The oil industry itself valued the 1137 New Mexico oil and gas wells completed in New Mexico during 1965 at $94 million—$83,553 a well. Costs ranging up to $500,000 are frequently ascribed to New Mexico wells in oil industry publications.

But of gravest concern to Ben Chavez, chief state tax commissioner, is the fact that the Tax Commission must rely, year after year, on the taxpayers themselves for production figures, well depths, tank and equipment inventory, pipeline dimensions, and mine and pit data for the setting of ad valorem assessments.

"Sometimes the figures don't change from one year to the next," said Chavez. "We have asked the legislature for funds to finance a systematic audit of these operations, fully convinced that auditing would produce many times its cost in new revenues. Thus far our pleas have fallen on deaf ears."

The result: All mining properties in New Mexico, exclusive of petroleum-producing properties, go on the assessment rolls at a total of $102,272,170; all nonpetroleum mineral production—evaulated elsewhere last year in excess of $225 million—went on the assessment rolls at $88,267,311—little more than the value ascribed to the state's 1966 copper production.

NEED TO INVEST TAX MONEY

Still more alarming to some is the fact that none of the revenues coming to the state from petroleum and other mining resources is being saved or invested for future generations.

Most of the funds from the extractive resources go into the state's general fund and public school financing for immediate use. In recent years, on the theory that severance taxes should be expended for something permanent and tangible, certain revenues from state severance assessments have been pledged to retire the bonds used to build new public buildings. The new capitol building in Santa Fe was constructed with severance tax bonds, and new buildings at various state institutions are being financed in the same way.

MONEY SHOULD BRING IN NEW PLANTS

John May, deputy director of the New Mexico Department of Development, believes a substantial share of the taxes generated by the mineral industries should be expended to establish replacement industries in New Mexico.

I've been preaching this doctrine in New Mexico for the last four years," said May. "Our natural resources are not in inexhaustible supply. As we produce, they are either being played out or reduced to low grade.

In New Mexico the ghost towns are actually more numerous than the live towns. They are examples of communities whose natural resources have been played out, communities which died because they had no replacement industry when mining failed.

Here in New Mexico the taxes on the individual are relatively low—the taxes you and **I** pay on our homes and our incomes. They are low because we are leaning too heavily on our extractive industries and using the taxes they pay to pay for today's schools and services.

If our oil and gas resources were played out today, that would mean $73 million more we would have to pay as individuals to provide today's governmental services. These taxes—or a good share of them—should be invested for future generations, against the day when there will be few, or no, natural resources to carry the load.

SHOULD CHANGE THE CONSTITUTION

May believes that Constitutional Amendment No. 1, offered to voters for approval Nov. 7, offers one way New Mexico can use its current resources to provide replacement industries for the future. The amendment, if approved, would authorize a State Industrial Authority to invest certain state funds in new industrial enterprises in various communities of the state.

And, on the subject of new industries, ask an oil company executive why his company won't locate its next oil refinery in New Mexico.

If he's studied the situation at all, he's bound to mention the manufacturers' privilege tax imposed by New Mexico—a tax which out-of-state refiners do not pay.

MINERAL WEALTH PLAYS IMPORTANT ROLE

Production of mineral wealth in New Mexico exerts a tremendous positive economic impact on the state and contributes decisively to an expanding system of governmental services.

But its impact could be greater.

New Mexico is bound to be an exporter, for it is blessed with far more than its proportionate share of abundance.

But when a state's exports are dominated by raw materials rather than the finished products they will produce, that state reaps only the minimal benefits of its production.

Those who are aware of the state's underground wealth, those familiar with the state's tax structure, those conscious of the almost-total absence of indigenous processing industries in the state, those aware of New Mexico's lagging personal income—all offer an abundance of ideas as to what could and should be done.

Ideas are so numerous and so varied that a mere classification would be difficult.

One of the most extreme proposals, and one of the harshest, calls upon the state to assume and exercise confiscatory power over the property of those corporations whose administrative decisions result in the involuntary unemployment and dislocation of large segments of the state's population.

But an approach more realistic and more painless is suggested by Walter Famariss of Hobbs: "We can get more processing in this state either by imposing penalties or offering incentives—or both." The penalties would imposed against those who insist on transporting unprocessed raw materials from the state. The incentives would be offered to make in-state processing more attractive economically.

Famariss is the oil refiner who went before the 1967 New Mexico Legislature and obtained special legislation to assure him a sufficient supply of New Mexico crude oil to keep his 4500-barrel-a-day refinery in operation.

NEED MAJOR TAX REFORMS

Most of the reforms suggested by others would take the form of taxes or incentives, most of which would be financed by the taxes generated by the state's extractive industries.

Tax proposals from those "in the know" fall into two categories: Corrective measures and punitive measures.

Here are some of the corrective measures proposed:

Application of a uniform severance tax on all the state's extractive industries with no exemptions and no deductions.

Advocates of this proposal point out that a severance tax is imposed for a single reason: to compensate the state and its people for irreplaceable wealth removed from the earth. The expense of extraction, they point out, does not mitigate the permanent loss to the state; there is ample opportunity to deduct legitimate production expenses in the corporate and personal income tax return.

Reforms that would proportion the tax burden more equitably between the petroleum industry and the extractors of solid-state minerals.

It is noted that New Mexico's petroleum industry, producing about 63 percent of the annual mineral product, is paying 85 to 90 percent of the taxes imposed on the state's mineral extractive industries.

The well-disciplined petroleum industry has not complained of this fact. The other mineral groups, on the other hand, complain that they are being taxed out of the market and protest that any heavier tax burden would put them out of business.

Administration of state tax laws by a single agency. The state's extractive industries are making their tax and royalty payments to four or more distinct agencies: The New Mexico Bureau of Revenue, the State Oil and Gas

Accounting Commission, the State Land Office, and the county treasurers of the several counties in which their properties or production are centered. Still another agency, the State Tax Commission, is responsible for most of the assessments.

Application of gross proceeds taxes uniformly on the sales of all extractive industries, without deductions, just as sales taxes are imposed against the distributive trades.

Repeal of the manufacturers' privilege tax. Those familiar with this tax insist that it discriminates against the manufacturer who processes New Mexico raw materials and does not apply to the out-of-state manufacturer processing the same materials.

The punitive taxes proposed by those concerned with New Mexico's colonial status take two forms:

An export tax imposed against all unprocessed New Mexico raw materials moving across state lines.

Those who propose such a tax would invoke a complex formula which would reduce the tax against those exporters maintaining sizeable payrolls in New Mexico. This would encourage partial processing of the raw product in the state where total processing would not be economically feasible.

Advocates of such a tax also believe it should be applied gradually. This, they believe, would avert the risk of abruptly losing an existing market for New Mexico raw materials. Under one proposal, the export tax would not be applied for at least a year after its enactment. Then it would be applied at a nominal rate, doubled the second year, tripled the third year, and steadily increased thereafter until the full authorized rate was in force.

The gradual application of the tax, it is reasoned, would enable the purchasers of raw minerals to adjust their plans and processing schedules.

An import tax, to be applied against finished goods, for which New Mexico offers ample raw materials, into the state.

Incentives proposed to encourage more in-state processing of New Mexico raw materials take several forms.

State Rep. John B. Mattson, R-Bernalillo, shares the belief that more of the taxes generated by New Mexico's mineral industries should be invested in the New Mexico Bureau of Mines and Mineral Resources for the general benefit and perpetuation of the mining industries themselves.

DETAILED GEOLOGICAL MAP NEEDED

One of Rep. Mattson's priority projects for the bureau would be a detailed geological mapping of the entire state. It is estimated that field studies for such a project would cost an additional $500,000 a year for a period of about five years.

"Industry is prone to invest in finished-product facilities near the source of supply if it is known the source is not short-lived," said Rep. Mattson. "New Mexico has been an exporter of raw materials and an importer of finished goods—an unhealthy economic balance."

John May, deputy director of the New Mexico Department of Development, believes that approval of Constitutional Amendment No. 1 by the state's electorate would be a good start in the direction of providing incentive for processing industries.

Amendment No. 1 would allow the use of state funds for loans to aid in the economic development of the state and create new job opportunities in New Mexico.

TAX INCENTIVES LURE INDUSTRY

May believes that processing industries compatible with the state's diminishing mineral resources could be developed under such constitutional authority, and he believes that the investment of a substantial portion of the state's severance tax receipts in such industrial development loans would be consistent with the philosophy under which the severance tax is imposed.

Many of those who would like to correct the relative absence of processing industries in the state favor an incentive to new industries in the form of tax waivers.Such proposals, if enacted, would free the management of new industrial enterprises from certain state tax obligations for a limited number of years—the first three to five years, which usually are the most difficult for a new enterprise.

Industrialists active in the selection of new plant sites generally decry such "tax favors," denouncing them as "bait" or "bribes." They usually insist that a better incentive is a good community, with good schools, progressive officials and a wholesome attitude toward industry.

But there are few in New Mexico today who question the influence of such favors on New Mexico potash producers. New Mexico, in a monopoly situation dating back to 1931, has imposed discriminatory severance and gross proceeds taxes against potash production.

But Canada offered three to five years of tax-free operations to American potash producers who would help develop the new potash fields in Southern Saskatchewan.

And Canada is where the New Mexico potash producers are going.

JOURNAL POINTS UP NEEDED CHANGES

The *Albuquerque Journal* has presented an exhaustive series of articles on New Mexico's mineral resources—their vastness, their current contribution to the state's economy, their depletion, their importance to state and local governmental budgets, and their potential as a foundation for the future industrial development of New Mexico.

Because of the enormity of the subject, however, the articles barely scratched the surface.

Nevertheless, the series of articles was strongly indicative of

—The state's need and opportunity for more processing industries which would give its people a greater enjoyment of their mineral wealth.

—The urgent need for geological studies to determine the state's mineral potential.

—Inequities in the state's hit-and-miss tax structure, particularly as applied to mineral resources and production.

—The apparent rapid depletion of particular mineral resources at the expense of future generations.

—A mandate for the state legislature to earmark more of the taxes generated by mineral industries for the perpetuation of those industries and for the establishment of replacement industries.

Facts brought out by the *Journal* should challenge New Mexico's legislative and administrative officials to examine the tax structure thoroughly and to come up with a program that is equitable, enforceable, and adequate.

They should also consider ways of inducing those now extracting minerals here to come up with additional in-state processing steps. New Mexico has too long watched its oil, gas, coal, uranium, and other minerals flow to other states, which in turn have reaped the profits from further processing.

It is time we told progressive American industrialists of our riches and urged them to give more than passing consideration to New Mexico, its resources and its multiplicity of plant sites in their planning for long-range expansion.

Exploration Hypotheses for Luis Lopez Mining District

by Max E. Willard
New Mexico Institute of Mining and Technology

Significant amounts of manganese oxide have been mined from the Luis Lopez district at the north end of the Chupadera Mountains, approximately six miles south of Socorro. Several mines were in operation between 1952 and 1958. Currently, however, only one deposit is being mined. Most of the surface exposures of manganese have been previously tested and no exploration or prospecting is presently being done. If future exploration and development of the district is to occur, a much more thorough knowledge of the genesis of the deposits and of the regional geology is required. For this reason the New Mexico Bureau of Mines and Mineral Resources has undertaken a detailed geological-geochemical re-examination of the district.

A new geologic and topographic map of the district, at a scale of 600 feet to the inch, is largely completed. From this, it is evident that structurally the Chupadera Mountains are an elevated and complexly faulted block of Tertiary volcanic rocks.

The oldest known volcanic unit is a latitic tuff. Above this is a series of rhyolite flows and pyroclastics. Typical welded tuff, crystal tuff, vitric tuff, tuff breccia, and coarse volcanic breccia are represented. Interbedded in these rhyolitic rocks is one relatively thin basaltic-andesitic flow. Several closely spaced fracture systems cut the volcanic pile and at places offset the Santa Fe and Popotosa Formations and the recent alluvium.

All the known economically important concentrations of manganese oxides occur in fault zones in a crystal tuff, and manganese is present in small primary cavities disseminated throughout the tuff. Psilomelane, hollandite, and coronadite are the predominant ore minerals.

As a result of earlier studies by Alfred T. Miesch, Donnel F. Hewett, and others, it was suggested that the manganese deposits of the Luis Lopez district are hypogene. This conclusion implies that the deposits are epigenetic and that the depositing solutions were derived from a subjacent source. On the basis of very limited sampling, it was also suggested that the percentage of lead in the ore minerals increased from south to north in the district. This apparent zoning in lead encouraged preliminary investigation for other elements. It is now known that as many as 31 elements are present in some samples; including the precious metals, tungsten, molybdenum, zinc, arsenic, and antimony. These data, it was thought, justified a hypothesis relating the manganese deposits to the epithermal zone of mineralization. Hence, it was postulated that at depth the mineralization might change to a barite-fluorite-precious metal-sulfide assemblage that would warrant exploitation.

During the current re-examination, most of the known manganese occurrences have been remapped and systematically sampled. Thorough chemical analysis of each of these samples is under way. The chemical data thus far collected suggest that the areal distribution of the minor elements in the ore is unsystematic and that there is little or no systematic variation through a vertical range of approximately 800 feet. In addition, the new geologic mapping has shown that the manganese mineralization is largely confined to one rhyolitic crystal tuff.

The information thus far collected suggests an alternate hypothesis for the origin of these deposits. It is clear that the mineralizing solutions were hydrothermal, but that they were epigenetic and derived from some subjacent source has not been demonstrated. Hence, it is possible that the manganese-bearing solutions were generated in the volcanic rocks containing the deposits; that is, the ore solutions and the volcanic rocks were essentially syngenetic. The physical and chemical characteristics of the deposits are similar to those of known volcanic hot-spring deposits. The widespread deutericlike alteration of the tuff and its association with disseminated manganese oxides suggest that they are genetically related.

If the deuteric-hot spring hypothesis is correct, then the deposits cannot be expected to continue at depth and the possibility of exploitable deposits of other metals below the manganese ore does not exist.

The future of exploration in the district ultimately depends on which of the two hypotheses is most convincingly supported by the collectible data.