BULLETIN 36

Mineral Resources of Fort Defiance and Tohatchi Quadrangles, Arizona and New Mexico

BY JOHN ELIOT ALLEN
AND ROBERT BALK

Prepared under contract for the Bureau of Indian Affairs
under the Navajo-Hopi Rehabilitation Act of 1950

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FRONTISPIECE

Plate 2. Cliffs of Entrada and
Summerville sandstone in Todilto Park.
Photograph by courtesy of New Mexico Sun Trails

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Preface

In their vast reservation, the size of West Virginia, some 70,000 Navajo people try to wrest a livelihood from the austere and arid, yet vividly beautiful, land. In any geographic classification, this region in northern Arizona and New Mexico would be considered submarginal for human occupation and advancement. Necessarily, innumerable human problems arise in such an environment, but most of them go back to that of increasing the productivity of the land and utilizing every resource to provide employment and a higher standard of living for these people in their own area.

In response to vigorous portrayal of this need, the Congress in April 1950 passed Public Law 474, generally known as the Navajo-Hopi Rehabilitation Act, "to make available the resources of their reservations for use in promoting a self-supporting economy and self-reliant communities, and to lay a stable foundation on which these Indians can engage in diversified economic activities and ultimately attain standards of living comparable with those enjoyed by other citizens . . ." The Act authorized appropriations of $88,570,000 to be expended over a period of 10 years. Of this amount $500,000 was set aside for "surveys and studies of timber, coal, mineral, and other physical and human resources . . ." The Secretary of the Interior was directed to undertake the program authorized by the Act. The work, under the annual appropriations made thus far, is administered by the Bureau of Indian Affairs.

In order to carry on the mineral survey, the Bureau of Indian Affairs, under authorization from The Secretary of the Interior, in the late spring of 1952 negotiated contracts with the University of Arizona and with the Board of Regents of the New Mexico Institute of Mining and Technology. In the latter contract the State Bureau of Mines and Mineral Resources, a division of the Institute, was directed to make a thorough mineral resource study of a specified area of 483.6 square miles, now known as Fort Defiance and Tohatchi quadrangles, on the border of Arizona and New Mexico, and to provide a geologic map and published report.

The scientists and engineers of the State Bureau of Mines and Mineral Resources have undertaken the tasks imposed by the contract with the energy and zeal that the spirit of the Act calls forth. They have worked with the Navajo people, as well as with the personnel of the Bureau of Indian Affairs, and have had constantly in mind as their objective all possible assistance to the Navajo people.

In line with the long-range viewpoint, as well as with immediate practical application, the State Bureau staff has endeavored to find and evaluate all possible mineral resources whether or not they may have current use or market. The carefully prepared geologic map and geologic descriptions and interpretations should serve as a guide to this area both now and in the future, no matter what turns the economy and the genius of our country may take. The authors have attempted to arrange the information in their report in such a way that parts needed by nonscientists can be understood by them, whereas the technical parts necessarily are written in the language of the scientists and engineers who may use them. No current standards of technical excellence have been sacrificed in this endeavor.

Eugene Callaghan

Nontechnical Summary

The Navajo people, living as close as they do to the earth, have a comprehension of geologic features and earth materials that might surprise the casual visitor. This is illustrated by the glossary of Navajo geologic terms appended to this volume. Navajos make excellent prospectors; they know their neighborhood thoroughly and, if shown samples of the desired substance, they can report quickly if it is exposed in their area. For this reason the writers feel that the material in this report on Fort Defiance and Tohatchi quadrangles is not so far removed from the people it is intended to serve as the uninitiated might think.

Following a brief introduction, this report first provides the economic data on mineral resources, including metals, nonmetals such as clay or sand, mineral fuels, and ground water. Second, the report provides a complete discussion of the geology, the succession of rocks from the oldest to the youngest, as well as their distribution through the area, and their influence on the scenery or topographic expression. Last, it includes special reports on certain scientific contributions, as well as statements on such things as climate, and tabular data that might interest certain readers.

Aside from widely distributed uranium and vanadium deposits, as well as minor copper, the Colorado Plateau, of which the Fort DefianceTohatchi area is a part, is not noted for its content of the ores of metals, and no body of ore of consequence was discovered in the course of this survey. Oxides of manganese were found in noncommercial amounts in a few places, but no uranium minerals were observed in spite of a few shows by the Geiger counter.

Nonmetals do occur in quantity in the Fort Defiance-Tohatchi area. Probably the most significant discovery in the course of this work was the vast quantity of bentonitic shale in the Chuska Mountain area. Shale of this type, if it has the required physical properties, is widely used for drilling mud in oil and gas fields. Tests made thus far on a small number of samples show this material to fall somewhat short of requirements. If suitable material is found, this shale may have a ready market in the nearby San Juan Basin fields. Sandstone such as has been used in construction of the attractive buildings at Window Rock is widespread in the area. Sands that might be used in the manufacture of certain grades of glass may occur in the area, though all sands tested thus far have neither the proper size distribution nor the low content of iron required for clear, high-grade glass. Stone suitable for crushing as road metal is limited largely to small masses of volcanic rock, though gravels on terraces along U.S. Highway 666 have been used. Baked shale from the vicinity of burned coal beds has been used for road-surfacing. Probably the most interesting of all nonmetallic materials in this area are the brightly colored fragments of the minerals, garnet (pyrope) and olivine, or peridot, which are found in or near the remnants of eroded volcanoes. Inasmuch as the host rock in some places is very similar to the kimberlite of South Africa which has been noted as a source of diamonds, it was natural to hunt rather intensively for these precious stones. None was found but, since the possibility was publicized during the course of this study, prospectors have been trenching in Buell Park in a systematic search for diamonds.

Of the mineral fuels, oil, gas, and coal, only coal as yet has been discovered. Formations that elsewhere have proved to be reservoirs for oil or gas have been eroded from the area west of Black Creek Valley. To the east of that valley, the situation is much more favorable, and a few tests with the drill have been made, notably in Todilto Park. The possibilities of discovering oil and gas have by no means been exhausted, and undoubtedly many additional tests will be made in the future.

Subbituminous coal of commercial thickness and grade (more than 30 inches thick and containing less than 12 percent ash) occurs in Tohatchi quadrangle east of Black Creek Valley. It was not possible in the time available for this study to estimate accurately the total amount of coal that might be recovered in a thorough mining operation, but at least 19 million tons in one bed more than 30 inches thick and containing an average of more than 11,000 Btu as mined can be expected. Thus adequate fuel for any local industry is present in the area. Mining of coal from this area for shipment to distant points cannot reasonably be expected until a major change takes place in the overall resources and industrial picture of the nation.

In this arid region the problem of water supply is the most acute of all resource problems. Owing to the dominating altitude (9,000 ft) of Chuska Mountain, a few short permanent streams do occur in the area, but their flow is not sufficient to support any extensive irrigation plan. Springs also occur in the mountain, but ground water drawn or pumped from wells must provide the bulk of water used in the area. Water occurs in the alluvial fill of some of the valleys and may be reached by shallow wells. In the eastern part of Tohatchi quadrangle, ground water is limited to sandstone beds, which may lie at depths of 1,000 feet or more, and to the surface alluvium. The addition of carefully located and properly drilled wells could add materially to the available water supply. Development of springs and the meager surface-water supply to prevent wastage also would help. Possibilities for increasing the ground-water supply vary greatly for certain parts of the area, and the reader is referred to the text of the report for this detailed information.

The entire Navajo country, vast as it is, is only a part of the great Colorado Plateau. For the most part this extensive region is characterized by accumulated layers of sedimentary rocks, sandstones, shales, and limestones, lying upon a floor of much older rocks which are designated either as igneous (granite, etc.) or metamorphic (gneiss, schist, quartzite, marble, etc.). The old floor, or basement, is well exposed in the deep trench of the Grand Canyon, but elsewhere the sedimentary cover is nearly complete. For the most part the sedimentary strata or layers are nearly flat, but here and there, in response to local upthrusts of the earth's crust, they are bulged upward in broad uplifts or folds. On the margins of these folds the beds may dip or slope away from the axis of the fold rather steeply (20 degrees or more). Such an uplift dominates the Fort Defiance-Tohatchi area and is known as the Defiance uplift.

The axis of this uplift trends nearly north in the western part of Fort Defiance quadrangle, so that the strata dip to the east and to the west from the central part of the bulge. At the north end of the uplift, the rocks dip to the north and at the south end they dip southward. The amount of uplift has been so great that near the center the basement floor itself is exposed as masses of quartzite in canyons. To the east the rocks continue to dip easterly for almost the width of Tohatchi quadrangle, so that successively younger rocks are exposed. However, at the east edge the eastward dip changes to a gentle westerly dip, producing a fold that is concave upward and is called a syncline, in contrast to the fold that is convex upward, called an anticline.

The great succession of stratified rocks shown on the geologic map both in their distribution and proper order, despite their thickness of more than 11,000 feet, does not represent all of geologic time. In fact, many long periods of time are represented simply by the contact between layers. However, it usually is possible to assign ages to the rocks that are in the column. The oldest formation which lies on the basement rocks is the Cutler, a series of red sandstone beds with shale partings; these beds probably were deposited by rivers on broad flood plains or on coastal plains of the Permian sea which lay to the south. The Permian is the last of the great periods of the Paleozoic Era; hence, rocks representing all earlier periods of the Paleozoic are missing. The quartzite is believed to be earlier than the Paleozoic. The Cutler is followed by the De Chelly, a thick-bedded sandstone with sweeping inclined stratification, which suggests that it was deposited as dunes on a coastal plain.

The De Chelly was followed by an unknown interval of time for which there is no nearby record. The next formation, known as the Shinarump, is a conglomerate made up of sand and bright, hard pebbles. It belongs to the Triassic period of the Mesozoic Era, the age of dinosaurs or giant reptiles. This formation appears over almost the full width of the Colorado Plateau, and almost everywhere it contains fossil plant remains, mostly swamp plant types, and the trunks of trees. All these features appear in Fort Defiance quadrangle.

The conglomerate formation is succeeded by more than 1,000 feet of shales, sands, gypsum, and minor limestone called the Chinle and likewise assigned to the Triassic. Since this formation consists largely of shale which weathers down and erodes readily, it commonly occurs in valleys and here underlies Black Creek Valley. The Chinle also may contain fossil trees, and the great Petrified Forest of Arizona is in this formation. Commonly the rocks are variably colored and where well exposed, as in the Painted Desert of Arizona, they provide colorful scenery.

Four succeeding formations, mainly colored sandstones, provide the vertical walls and spectacular scenery of the east side of Black Creek Valley and of Todilto Park. All of these are assigned to the Jurassic or middle period of the Mesozoic Era. The lowermost, the Wingate sandstone, is a weak formation and is generally covered. The next formation is the Entrada sandstone, which is over 200 feet thick, and stands out in such prominent cliffs as are shown in the Frontispiece of this volume (pl 2). This is the familiar sandstone of Window Rock and Todilto

Park. The Entrada may be overlain by a limestone bed about 15 feet thick, although the latter may be absent in places. This is one of the prominent uranium-bearing formations of the Grants area in New Mexico. It is followed by another colored sandstone, the Summerville, which in turn is overlain by the Morrison formation. The Morrison contains two members, the Recapture shale and the Westwater Canyon sandstone. Elsewhere in the Colorado Plateau the Morrison is a prominent bearer of uranium.

The Morrison is the last and uppermost of the colorful (mainly shades of red) sandstones that form the cliff slopes on the east side of Black Creek Valley. In comparison, the succeeding formations are all of drab appearance, shades of yellow or gray, with dark shale beds. These rocks are all of Upper Cretaceous age, the last of the Mesozoic periods. The Lower Cretaceous is missing in this region. The basal Upper Cretaceous formation is the Dakota (?) sandstone which commonly appears as a dark rim at the top of the succession of Jurassic sandstone cliffs. It is followed by the Mancos shale which, being a weak rock, mainly underlies a valley. The Mancos, which contains marine fossils, is overlain by a thick succession of sandstones and shales referred to in this report as the Mesaverde group. The commercial coal seams occur in the lower part of this group of formations, which are listed separately on the geologic map (pl 1). The highest and youngest of the Cretaceous formations is the Tohatchi formation which contains bentonitic clay and which is exposed on the south and east face of Chuska Mountain. The Age of Reptiles ends in this area with the Tohatchi shale. Subsequent formations belong to the Age of Mammals (the Tertiary) and the Age of Man (the Quaternary).

After the deposition of the last Cretaceous formation, the Defiance uplift was formed, permitting erosion of the upwarp almost down to the present level of its summit. All rocks—however uplifted, faulted, and folded at the end of Cretaceous time—were eroded to an almost level surface. Near the close of Tertiary time this surface was covered by water-laid sand and shale, and later by windblown sand, to form the Chuska sandstone, the formation that caps Chuska Mountain. With the great uplift of the Colorado Plateau and the establishment of drainage to the sea, the surface marked by the Chuska sandstone was dissected, and later the present drainage system was established. Erosion has been continuous in the uplands, but with dimatic changes the valleys were for a time choked and filled with debris to form valley plains, which again within historic time are being dissected, with accompanying removal of the valley fill. Notable features of late geologic history are the great landslides on the east side of Chuska Mountain. Seemingly, at the close of the last period of glaciation, so much rain and snow fell in this area that the shale under the Chuska sandstone was soaked to the extent that sliding of great masses of the sandstone was facilitated.

Shortly after the deposition of the Chuska sandstone, a group of volcanoes formed along an east-northeast zone from Fluted Rock at the west edge of Fort Defiance quadrangle to Beelzebub in Todilto Park. Outside the two quadrangles there were many more of these volcanoes. Erosion has reduced most of the cones to mere stumps. However, these eroded remnants (such as The Beast or Buell Park) show many very interesting features and in themselves are striking features of the landscape.

Buell Park is a saucer-shaped depression in sandstone owing its origin to erosion and removal of a volcanic tuff which is less resistant than the surrounding rock. Within the depression are ribs and prominences of more resistant volcanic rock. We may be permitted to reconstruct the history of Buell Park in this way: Volcanic gases from deep within the earth work their way upward through the rock. When the weight of the overlying rock no longer can contain the pressure of the gas, the gas explodes, blasting the rock out of its path and forming a crater or bucket-shaped depression in the sandstone. As volcanic activity continues, this broad pit is filled with volcanic debris consisting of fragments of old rocks brought up from below, as well as with lava and crystals from the igneous source itself. In this way a volcano, perhaps 1,000 feet high, was built above the land surface. Some liquid lava was forced up through this cone of debris to form dikes and flows or to congeal within the throat of the volcano. After the end of volcanic activity, erosion not only removed the cone and the flows but cut down well below the land surface to form the depression we now know as Buell Park. The volcanic tuffs are now disintegrated and the brightly colored crystals and fragments of garnet, peridot, and other minerals have been released and may be picked up on the surface. Buell Park was probably the largest of the volcanoes in the Fort Defiance-Tohatchi area, but the other volcanoes doubtless had much the same history.

The Special Reports at the end of the volume provide the results of detailed scientific investigations and list tabular data which may be of interest to specialized investigators. The report on the petrology of sedimentary rocks is a notable contribution in this field. The clay fraction from samples of all the sedimentary rocks was tested by thermal analysis, X-ray diffraction, and other techniques to determine the dominant type of clay mineral. It was found that in this geologic section the clays can be grouped in a definite order with certain breaks. In general, clays of marine origin differ from those of continental origin. Also there are changes in the proportions of the "heavy" minerals, the groups that may be separated from the quartz, feldspar, and clay of the rock by means of their specific gravity. The techniques and results developed in this study may aid materially in correlating samples from oil or water well tests.

Four measured sections are described in detail, so that the minor characteristics of the rocks of the Menefee and Crevasse Canyon formations are on record. A seismic survey in Buell Park failed to outline the depth of the caldera, so it is assumed that it may have vertical walls.

Other reports list climatic data for the area, plants growing in the various life zones, a glossary of technical terms used, and a list of some of the Navajo words which approximate geologic terms. A bibliography and index complete the report.

Technical Abstract

The 15-minute Fort Defiance and Tohatchi quadrangles lie south of latitude 36 degrees and include a part of San Juan Basin, New Mexico, as well as the bordering region in Arizona. The area contains a part of the synclinal "Gallup embayment," a part of the Defiance uplift and monodine, the southern end of the high Chuska Mountain plateau, and the north end of the lower Manuelito Plateau. Smaller features are the Todilto Park dome and Buell Park diatreme with its central kimberlite-tuff plug. Several dikes and smaller central intrusives are aligned in an east-northeast direction.

Altitudes range from 6,200 feet in Chuska Valley along the eastern border of the area to more than 9,000 feet on Chuska Mountain. The climate is semiarid; life-zones range from upper Sonoran to Hudsonian.

No mineral resources are being exploited currently in the area. Coal and nonmetals have commercial possibilities, but metallic minerals found in the course of this survey consist solely of a few traces of manganese oxides in sandstone concretions. In spite of the fact that elsewhere the formations exposed in this area are uraniferous, so far only one locality has been found sufficiently radioactive to affect the Geiger counter, and no uranium mineral was seen. Large deposits of bentonitic shales which occur in the Tohatchi formation on the slopes of Chuska Mountain may be of value as well-drilling muds, though tests thus far have not been favorable. Sands which possibly could be beneficiated and used for a local green glass industry occur in the Chuska sandstone. Semiprecious stones, garnet and peridot, which have been used to a slight extent for native jewelry, are associated with some of the igneous rocks, particularly at Buell Park. Coal beds of commercial thickness and extent occuring in the Crevasse Canyon formation, are adequate for any local industry. No oil or gas has yet been discovered in these quadrangles, but formations which elsewhere are petroliferous underlie most of Tohatchi quadrangle. Water occurs in the Chuska sandstone, which supplies the perennial springs along the west side of Chuska Mountain, and in Cretaceous sandstones, which can be tapped as underground water sources in Tohatchi quadrangle.

The sedimentary sequence is 11,000 to 12,000 feet thick. It has been divided into 19 major and 16 subordinate units. Four igneous rock-types are described. Pre-Cretaceous rocks include Precambrian (?) quartzite, exposed only in two canyons northwest of Fort Defiance; Permian Cutler formation and De Chelly sandstone (1,060-1,300'); Upper Triassic Shinarump conglomerate and Chinle formation (1,0001,350'); Lower Jurassic Wingate sandstone (80-265'); Upper Jurassic Entrada sandstone, including Carmel silty facies (220-293'); Todilto limestone (0-14'); Summerville formation (340-367'); and Recapture shale and Westwater Canyon sandstone members of the Morrison formation (464-857'). Tongues of Cow Springs sandstone come into the area from the south within the Recapture shale and at the top of the Summerville formation. A few thin lenses of maroon shale appearing above the Westwater Canyon sandstone possibly are equivalent to the Brushy Basin shale to the north of the area.

Upper Cretaceous rocks include 4,800 to more than 6,100 feet of marine and nonmarine sediments which have been mapped as the Dakota (?) sandstone (218-253'), Mancos shale (630-750'), and Mesaverde group (4,000-4,825'). The Mesaverde group has been divided into five formations and several members, as follows: Gallup sandstone (100-400'); Crevasse Canyon formation (252-410'), which includes the Dilco, Dalton sandstone, and lower Gibson members; Point Lookout sandstone (0-365'), which includes the Satan tongue of Mancos shale and Hosta sandstone tongue; Menefee formation (2,300'); and Tohatchi formation (1,350' plus), subdivided into lower carbonaceous and upper bentonitic members. The sandstone members of the Mesaverde group thicken and thin rapidly; they split and pinch out or are replaced by siltstone within short distances.

Tertiary sedimentary rocks consist of the Pliocene (?) Chuska sandstone (1,100' plus), which was deposited unconformably upon the beveled edges of rocks ranging from the Summerville formation to the Tohatchi formation.

Nine igneous plugs, with associated discontinuous dikes, penetrated the sedimentary rocks in late Tertiary time. Buell Park is a diatreme characterized by a ring dike, composite plugs, and kimberlite and lapilli tuff. North of Tohatchi quadrangle, at Washington Pass, a similar igneous mass cuts through the Chuska sandstone, and plugs in the mapped area may have been emplaced after the erosion of much of the Chuska sandstone. However, the igneous activity was terminated before the present major valleys were incised into the post-Chuska rejuvenated "Zuni erosion surface." The earliest igneous rocks are kimberlite tuff and lapilli tuff, composed of partly altered olivine (fa8-11), enstatite, chrome diopside, pyrope garnet, actinolite, ilmenite, magnetite, titanclinohumite, and a pale-green, aphanitic groundmass of antigorite and indeterminable, minute mineral fragments. Xenoliths in the tuff include various siliceous crystalline rocks, and cognate fragments of peridotites. Fragments of the surrounding sedimentary rocks are rare. Closely associated are plugs and dikes of minette and minette-breccia, composed for the most part of diopside, biotite, sanidine, and variable amounts of brown glass, possibly with small amounts of olivine and leucite in places. Leucocratic phases in Buell Park approach trachyte in composition. No contact effects were seen at kimberlite tuff contacts, but the minette has vitrified the sandstones in several places. The trachytic phases of Buell Mountain, Fluted Rock, and the minette plug of Zilditloi Mountain may have approached the surface closely, but true surface flows are lacking.

Quaternary sediments consist of Pleistocene and Recent terrace and pediment gravels, which occur at several elevations, and of landslide debris which is widespread around the south and east sides of Chuska Mountain and below the Gallup sandstone cuesta along the southern junction of the two quadrangles. These units rarely reach 50 feet in thickness. Recent alluvium, called the Nakaibito formation (0-50'), occupies the wider valley bottoms.

The sedimentary sequence has been folded to produce the broad, north-plunging Defiance uplift, whose axis passes through the center of

Fort Defiance quadrangle, and the north-plunging Nakaibito syncline, whose axis lies just east of the *center* of Tohatchi quadrangle. The Todilto Park dome is a subordinate fold whose long axis strikes N. 15° E. Dips as steep as 35 degrees occur on the eastern flank, but to the west the beds dip gently into the shallow Zilditloi syncline, which swings to the southeast to form a minor trough in the Nakaibito syndine terminating near Mexican Springs. Another minor crenulation near the center of the southern edge of the area represents the northern termination of the syndine which has brought down the coals mined at the Window Rock coal mine in the quadrangle adjoining the Tohatchi on the south. On the east flank of the Nakaibito syncline, a wide structural nose may reflect the northwesternmost extension of the Zuni uplift.

Fracture systems are prominent in the Permian formations. Vertical northeasterly-trending joints transect the southwestern and central parts of the Defiance uplift within the map area. Northwest-trending fractures extend from the vicinity of Sawmill to the northwest corner of Fort Defiance quadrangle. Conceivably these fracture systems are radial tension joints related to the Buell Park diatreme. Steeply west-dipping joints are a feature of the east slope of the Defiance uplift. They are probably tension joints related to tangential stretch in the uparched zone. The Mesozoic sandstones on the east side of Black Creek Valley locally display slip zones with small displacements, and east-west striking striae. Some east-west striking joints accompany the zone of igneous plugs extending from Fluted Rock to Beelzebub.

The area lies wholly within the Colorado Plateau Province, and its physiographic divisions reflect the structures and composition of the underlying rocks. On the west, the Defiance Plateau is essentially a broad anticlinal arch in the Permian and Triassic rocks pierced by the Buell Park diatreme near its axis. It is bounded on the east by the monoclinal Black Creek Valley, incised in the soft Triassic Chinle shales. Todilto Park is formed by a local anticlinal arch which exposes the Chinle along its axis. The Manuelito Plateau, bounded on the west by cliffs of east-dipping Jurassic sandstones, and on the east by badlands and east-dipping cuestas of Point Lookout sandstone and sandstones of Menefee formation, is essentially a structural terrace imposed on the Defiance monoclinal structure. Chuska Valley is carved in the gently-dipping Menefee rocks, and is divided into two parts, the western badlands, terraces and pediments, and the eastern alluviated portions. Chuska Mountain consists of the nearly flat high plateau, underlain by Chuska sandstone, with the subdivisions of lower-lying structural terraces on the west and landslide areas on the south and east. Subsequent to the long erosional epoch which extended throughout nearly all of Paleozoic time, the depositional history of the area was initiated by Permian continental flood-plain and sand-dune deposition forming the Cutler and De Chelly shales and sandstones. Lower Triassic (Moenkopi) beds are missing in the area, and Upper Triassic deposition commenced with a widespread but thin sheet of coarse conglomerate (Shinarump) followed by thick shale and minor sandstone sequence (Chinle) representing river flood-plains and swamps. Above these rocks, with only an inconspicuous disconformity, lie Jurassic units consisting of thick, massive-weathering, crosslaminated and predominantly red-colored sandstones and subordinate shales. These rocks represent a widespread and thick accumulation of river flood-plain and sand-dune sediments interrupted by one period of lacustrine or marine deposition (Todilto) of sandy limestone.

Epeirogenic subsidence, following a period of nondeposition or erosion which lasted throughout early and middle Cretaceous time, permitted the first definitely recorded advance of the sea, from the northeast, over the area. The lowermost Upper Cretaceous rocks consist of siltstone, coal, and thin sandstone of the Dakota (?) formation, representing the lagoons. The thicker cuesta-making sandstone represents the offshore bar and beach, the marine (Mancos) shale the deeper marine deposits. Repeated transgression and regression of this shoreline across the area from the northeast to the southwest, with influx of abundant silt and sand from highlands to the southwest, led to a complicated series of intertonguing sandstones, siltstones, and coals which make up the Mesaverde group of rocks. Within this area marine deposits occur twice during Mancos and Satan transgressions; apparently the shoreline did not quite reach the area during the Mulatto or Lewis transgressions.

Post-Upper Cretaceous (Laramide) folding produced the structures previously listed. Subsequent extensive Tertiary erosion formed a widespread surface of low relief (the "Zuni erosion surface") upon which was deposited the dominantly eolian Chuska sandstone of Pliocene (?) age. Later, the Chuska sandstone was variably eroded and the Zuni erosion surface was exhumed over large areas. Volcanic activity penetrated this surface and formed the igneous features previously discussed. Quaternary uplift and gentle westward tilting superposed established drainages across the folds, incised numerous subsequent valleys, and produced several series of sloping pediments and terraces. This postChuska degradation may have removed over 1,000 feet of Chuska sandstone and up to an additional 2,000 feet of Cretaceous rocks from much of the west half of San Juan Basin.

During glacial pluvial epochs (Wisconsin) and before present canyons and badlands were completely formed, landslides developed around the south and east escarpments of Chuska Mountain, especially where the sandstone was underlain by the upper Tohatchi bentonitic shales. Following the late Pleistocene and Recent cutting of the present canyons and badlands, alluviation filled the lower stream-courses with Nakaibito sediments, and, in historical time, gullying of this fill has begun again.

The petrology of a section of sedimentary rocks that range in age from Precambrian through part of Cretaceous was studied in detail. Chip samples from nearly all of the stratigraphic units were disaggregated; the silt-clay size fraction was removed by elutriation, and the remaining sediment was mechanically analyzed.

The median diameter, angularity, solubility, and coefficient of sorting were determined from each sample. The percent of feldspar and heavy minerals in the .125 or .062 mm size fractions also was determined. The frequency percent of the heavy minerals was determined by grain counts. Differential thermal analyses were made of all the silt-clay concentrates, and many of the samples were tested by X-ray diffraction and staining.

Differential thermal analyses suggest that the De Chelly and Chinle formations are the product of uninterrupted sedimentation, partially in a marine environment. The heavy-mineral assemblage and the abundance of montmorillonite in the Chinle indicate that in this area the Chinle is a mixture of volcanic and nonvolcanic material.

The Jurassic sediments present many of the features of the rocks above and below them. No major change in the mineralogy occurs across the contact between the Jurassic and Cretaceous formations.

The minerals of the rocks from the upper part of the Westwater Canyon sandstone through the lower part of the Mancos shale appear to be the remains of preexisting sediments. Above the Mancos shale they appear to have been derived from a crystalline source.

The observed changes in the mineralogy and physical state of the rocks in the studied section, may prove to have a restricted range in time, and hence may aid materially in subsurface correlations.

Two measured sections in the Menefee formation, located about 2 miles apart, were described in detail in order to determine lateral variation of the beds within relatively short distances. Comparison of the descriptions of these sections (pl 11, nos 5 and 6) and of an additional section nearly 4 miles farther south (pl 11, n 9) bring out two features: first, that the sandstone units thicken and thin and disappear within short distances, and hence cannot with assurance be correlated over even these short distances without walking them out along the strike; and, second, that the ratio between the sandstone and the shale and siltstone changes southward from about 1:4 to more than 1:3. Two sections of the Crevasse Canyon formation were also described.

A seismic reconnaissance in Buell Park was made in an attempt to determine whether the caldera has vertical walls, or whether it is saucer-shaped and has a bottom, possibly approximating the Precambrian surface. Results were not conclusive.

Climatic data from 2 stations in the area and from 3 other nearby stations indicate that the climate, although variable by reason of elevation differences, consists of temperature average from 25 to 30 degrees in January to 65 to 75 degrees in July. The average annual precipitation is 10 to 13 inches, more than half of which falls between April and September.

A complete list of plants in the area, a glossary of technical terms employed, a list of Navajo words used for geologic terms, and a bibliography and index complete the report.

Explanation of Plates 3-10

PLATE 3

AIR VIEWS OF BLACK CREEK VALLEY AND TODILTO PARK

A. Air view across Red Lake, looking northeast. 1. Green Knobs, 2. Outlet Neck, 3. Todilto Park, 4. Chuska Plateau.

B. Air view across Black Creek Valley, just south of Red Lake, looking northeast. 1. Outlet Neck, 2. Zilditloi Mountain, 3. The Beast, 4. Unnamed dike.

PLATE 4

SEDIMENTARY ROCKS AND IGNEOUS PLUGS

A. Intensely jointed Precambrian (?) quartzite, on north bank of Blue Canyon Wash, overlain unconformably by horizontal Cutler formation.

B. View northeast across mouth of Twin Buttes Wash from outcrop of Wingate sandstone. Tall cliffs in middle distance are Entrada formation overlain, in left distance, by Summerville formation. Pine-covered slope underlain by sand and shale lenses of Morrison formation. Ledges of Dakota (?) sandstone at summit, rest on thin Westwater Canyon sandstone.

C. Kimberlite tuff, near center of Buell Park.

D. The Beast, a plug of minette breccia, viewed from the southwest. Erosion of sandstone xenoliths has caused reentrants in cliff.

PLATE 5

UPPER CRETACEOUS FORMATIONS

A. Type locality of Tohatchi formation west of Tohatchi, looking northwest to northeast. Bentonitic member (Ktu) overlying sandstone and carbonaceous shale member (Ktl); Menefee formation (Kmf) below. Chuska Peak in upper left; Chuska Mountain on skyline at right.

B. Coal beds totaling 18 feet thick on South Fork of Catron Creek in the lower Gibson member of the Crevasse Canyon formation.

C. No. 5 coal bed 4 feet thick on South Fork of Catron Creek.

PLATE 6

CENOZOIC FORMATIONS

A. Chuska sandstone (Tc) overlying upper bentonitic member of Tohatchi formation (Kt) at type locality of Tohatchi 3 miles north of Tohatchi. Dashed line marks basal conglomerate. View northwest.

B. Twin Buttes, an outlier of Chuska sandstone lying unconformably upon Gallup sandstone south of Todilto Park. View northwest from Point Lookout cuesta on north rim of Crevasse Canyon.

C. Fluviatile lower member of Chuska sandstone above trail south of Chuska Peak.

D. Nakaibito formation north of ford in Todilto Park.

PLATE 7

SPECIAL FEATURES OF SEDIMENTARY AND IGNEOUS ROCKS

A. Polygonal cracks in top of Summerville formation, 11/2 miles southwest of Zilditloi Mountain.

B. Lower member of Tohatchi formation 3½ miles west of Tohatchi. Note dark carbonaceous layers in shales between thin sandstones.

C. Steep layering in lapilli tuff near southeast border of Green Knobs plug.

D. Cross-sections of steep columns of minette forming fiat top of Fluted Rock. View north-northwest.

PLATE 8

SPECIAL FEATURES OF SEDIMENTARY AND IGNEOUS ROCKS

A. Channel sandstone units near base of Menefee formation, 2 miles south of Crevasse Canyon. View north.

B. Concretions in channel sandstone of Menefee formation, half a mile east of Crevasse Canyon.

C. Beelzebub, a minette breccia plug intruding Entrada sandstone in the south part of Todilto Park. View southeast.

PLATE 9

PHOTOMICROGRAPHS OF IGNEOUS ROCKS (Bar scale equals 1 mm)

A. Kimberlite tuff from central hill, Buell Park. Olivine (o), partly or wholly replaced by aggregates of antigorite. Fragment of quartzite xenolith with iron oxide cement in lower right-hand corner. Dark groundmass is antigorite with various other minerals in minute grains. Grain of enstatite (e) near center. Plane-polarized light.

B. Kimberlite tuff from central hill, Buell Park. Crystal of chrome-diopside (upper left-hand corner), and 2 fresh olivines (o) in antigorite shell. Groundmass stained by iron oxides. Plane-polarized light.

C. Xenolith of peridotite from Green Knobs. Crystals of olivine (o) and enstatite (e) crossed by long blade of antigorite (a). Earlier antigorite forms dark veneers along cracks in olivine. Plane-polarized light.

D. Xenolith of peridotite from Buell Park. Olivine anhedra with excellent cleavage parallel (010), crossed by blades of antigorite. Plane-polarized light.

E. Minette of ring-dike at Buell Park. Phenocrysts of diopside and biotite (above center) with shell of black iron oxide, in groundmass of glass and minute sanidine laths. Large diopside contains interpositions of glass. Plane-polarized light.

F. Trachytic phase of minette from highest ledges of Buell Mountain. Essentially a felt of sanidine laths with phenocrysts of diopside (center and lower right) and biotite (upper *left).* Plane-polarized light.

PLATE 10

PHOTOMICROGRAPHS OF IGNEOUS AND SEDIMENTARY ROCKS

A. Minette from Fluted Rock. Clear, colorless sanidine crystals enclose innumerable small grains of diopside, biotite, and ore. Phenocrysts of biotite (dark plates) and diopside. large dark area in center is brown glass. Plane-polarized light.

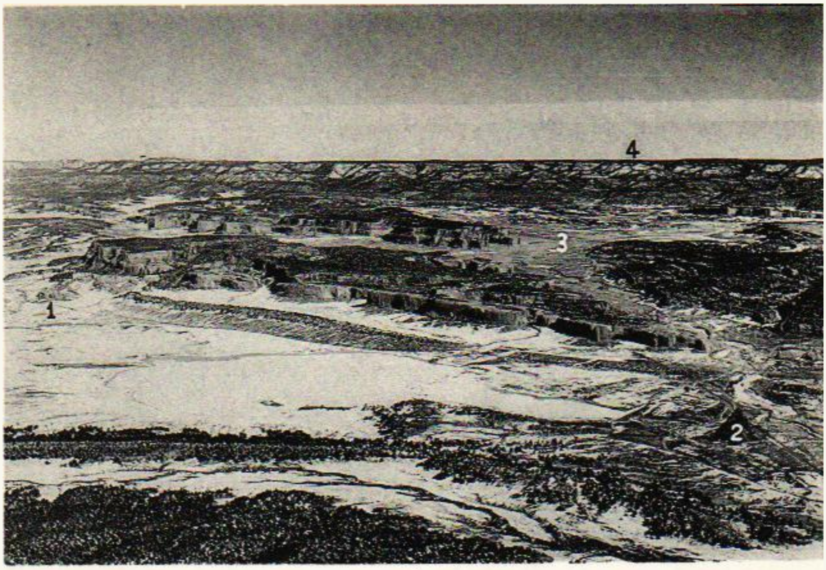
B. Same area as in A, showing size of sanidine crystals. Crossed nicols.

C. Trachybasalt from south base of Zilditloi Mountain plug. Brown glass encloses senate phcnocrysts of diopside and sparse biotite. Plane-polarized light.

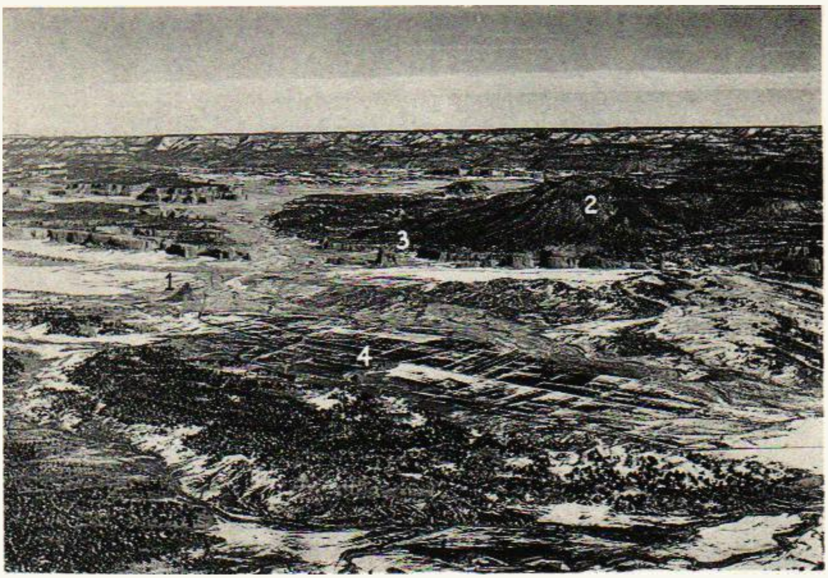
D. Border of silicified pebble in Shinarump conglomerate, 2.9 miles north of Fort Defiance. Fine-grained quartz mosaic extends from pebble (lower left) into matrix of conglomerate (upper right) across megascopically sharp border. Several elastic quartz grains survive. Quartz veinlet does not follow pebble border. Crossed nicols.

E. Sandstone lens in Shinarump conglomerate, 3 miles north-northeast of Fluted Rock. Cement partially replaced by iron oxides. Core (lower left half of field) with carbonate cement is free of iron oxides. Plane-polarized light.

F. Calcareous concretion in tufa lens in alluvium, 41/2 miles northwest of Fort Defiance. A few elastic quartz grains in matrix of minute calcite anhedra. White circular patches are chal-cedonic quartz in groups of radiating fibers. Crossed nicols.



A

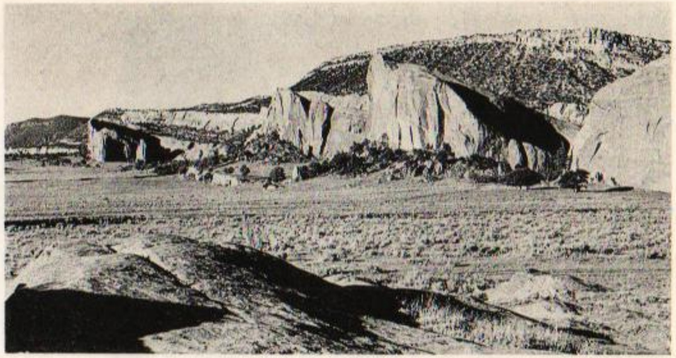


B

Plate 3: Air views of Black Creek Valley and Todilto Park.

Photographs by Sherman Wengerd, University of New Mexico.

A



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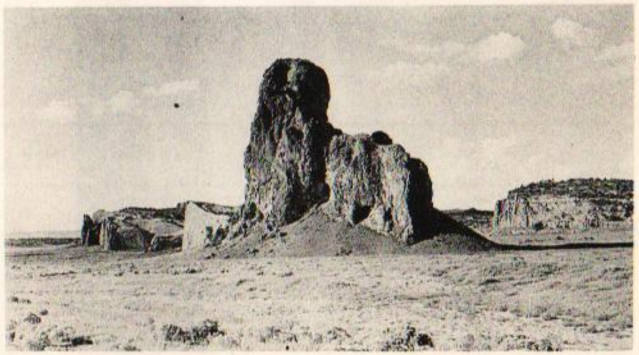
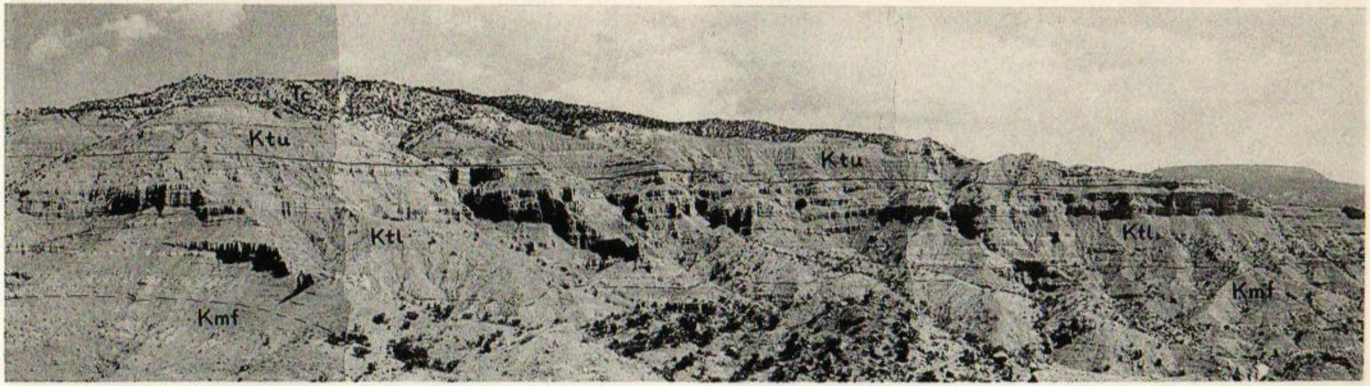


D

Plate 4: Sedimentary rocks and igneous plugs.



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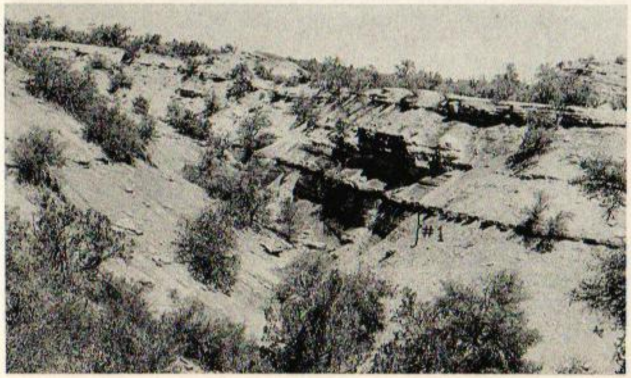

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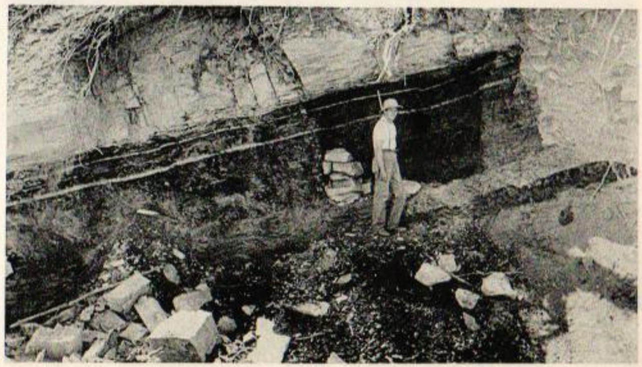
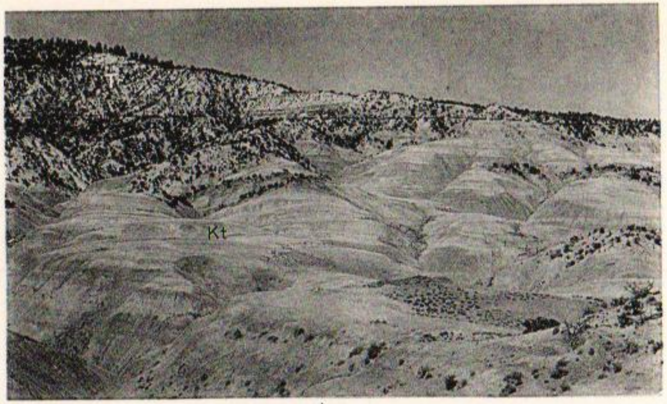


C

Plate 5: Upper Cretaceous formations.



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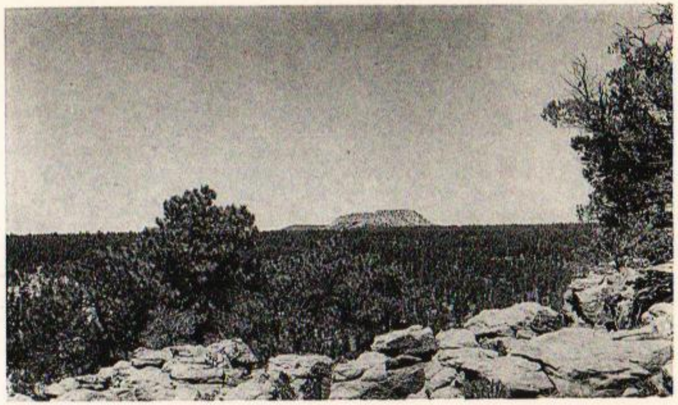

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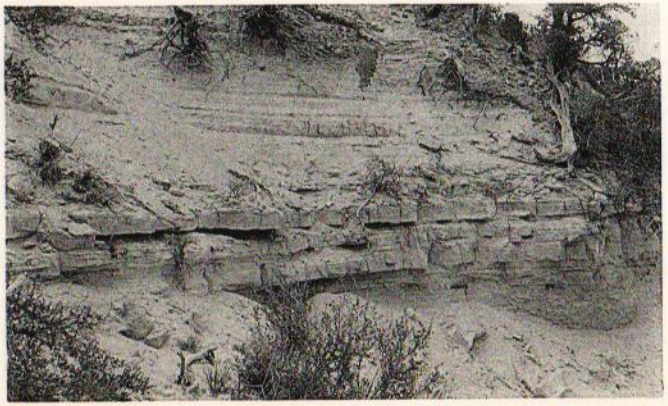

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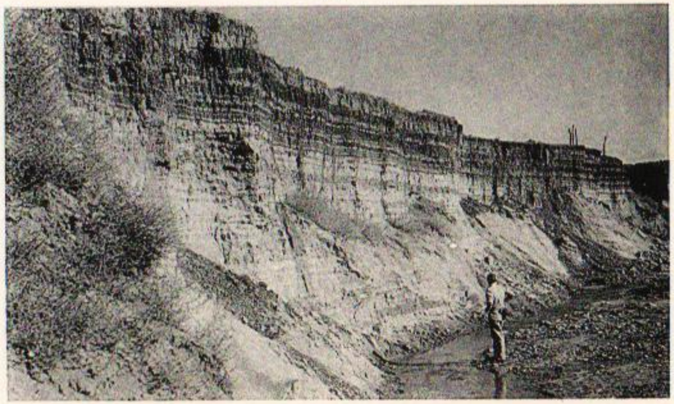

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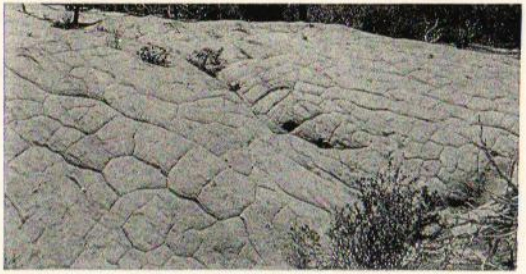
Plate 6: Cenozoic formations.



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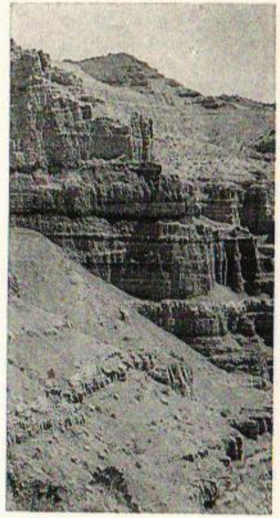

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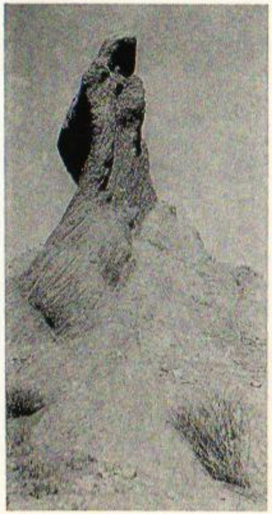

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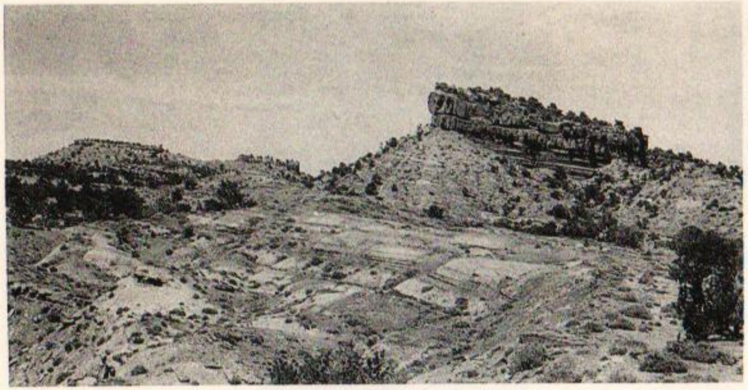
Plate 7: Special features of sedimentary and igneous rocks.



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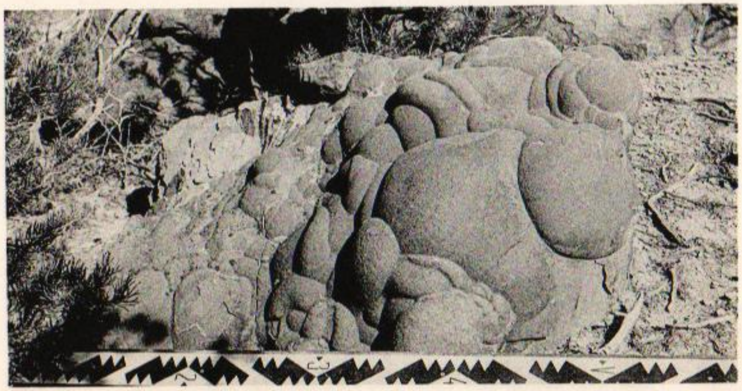

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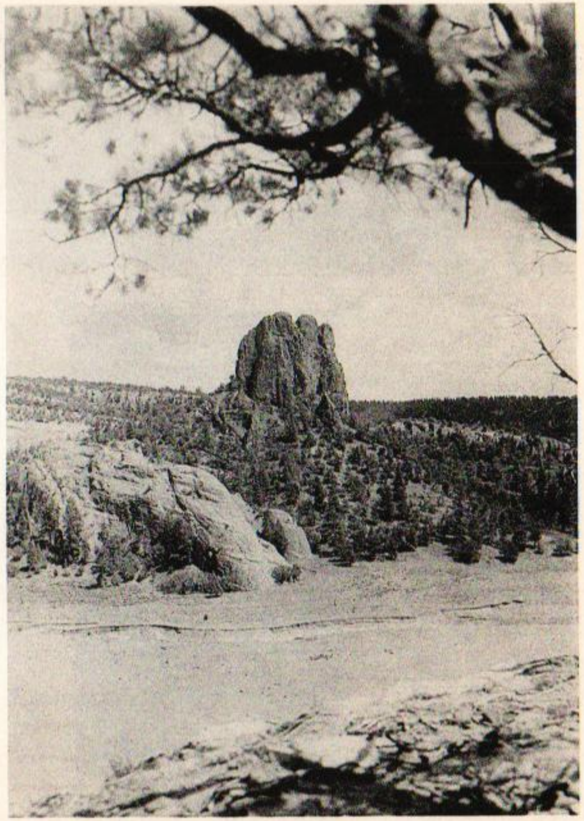

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Plate 8: Special features of sedimentary and igneous rocks.

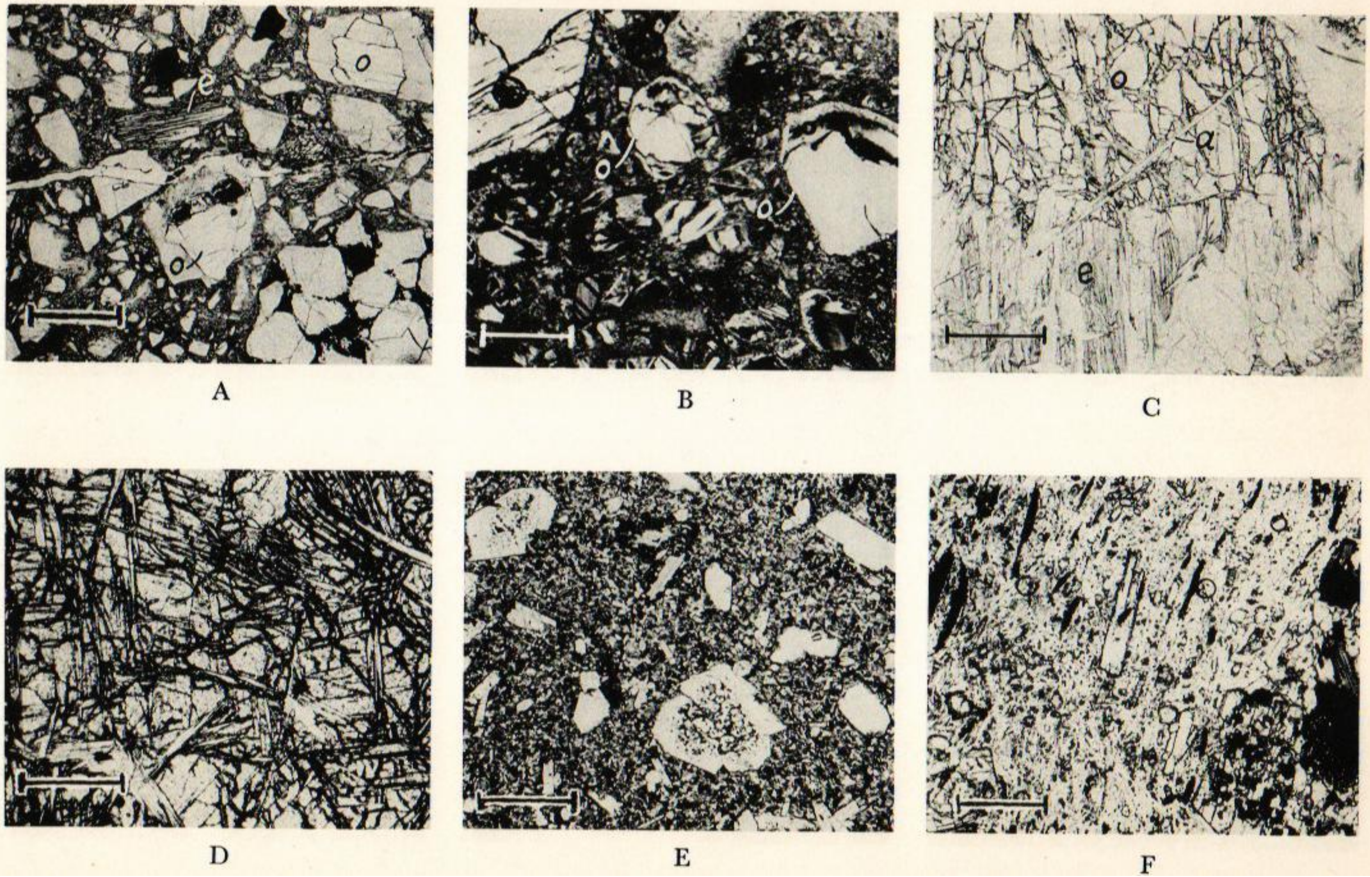

Plate 9: Photomicrographs of igneous rocks.

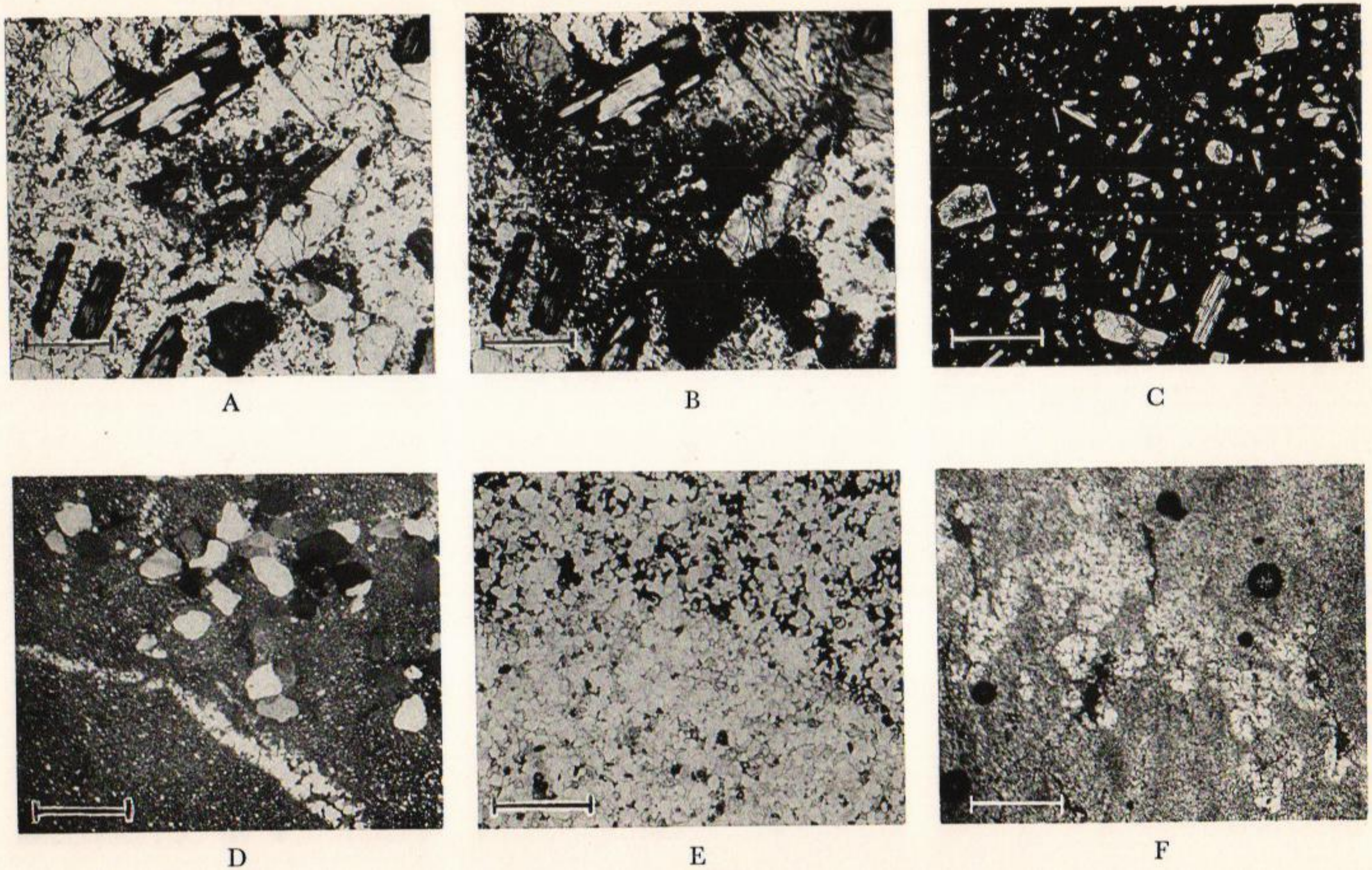

Plate 10: Photomicrographs of igneous and sedimentary rocks.

Introduction

PURPOSE AND SCOPE

The results of that part of the mineral survey of the Navajo Reservation for which the New Mexico Bureau of Mines and Mineral Resources was responsible under the terms of its contract of June 1952, are set forth in this report. The first objective of the report is to provide all pertinent information that was secured on mineral resources and ground water which may have actual or potential value to the Navajo people. A second objective is to show the distribution in space and time of all rock units contained in the study-area by means of a geologic map and sections, as well as by carefully prepared descriptions and interpretations in the text. This material provides the geologic setting for all possible resources, both those currently known and those which may be discovered in the future. The geologic data provide guidance for future prospecting and exploration in the Fort Defiance-Tohatchi area, as well as assistance to others who may carry on similar investigations in nearby parts of the Reservation.

As no accurate topographic base was available on which to portray the geology, it was necessary to use the available photomosaics of the Soil Conservation Service. Inherent inaccuracies necessarily exist in these mosaics, but they do not alter the geologic picture materially. The geologic data can be transferred from the individual photos to the topographic maps when such maps become available.

METHODS OF INVESTIGATION

This study is the result of teamwork on the part of several geologists and engineers of the Bureau of Mines and Mineral Resources, each contributing from the vantage point of his specialized knowledge and experience both in New Mexico and in other parts of the world. The work was under the immediate direction of John Eliot Allen, who mapped Tohatchi quadrangle and studied the coals and clays of that area. Robert Balk mapped Fort Defiance quadrangle and made an intensive study of the igneous rocks. Samples from the entire sequence of sedimentary rocks were studied in the laboratory by M. E. Willard, utilizing the most modern techniques. Other special mineral studies were made by M. S. Sun. The data on ground-water resources were secured by F. X. Bushman. Assistance was provided by other members of the staff.

The geology was mapped in the field on air photo contact prints at scales of 1/31,680 and 1/20,000 and transferred to the photomosaic, which has a scale of 1/48,000.

Though it is common practice to label each delineated area of a geologic formation with the appropriate letter symbol, it was found that for the geologic map (pl I) an abundance of letter symbols would obscure the photomosaic base unduly. Therefore, only enough symbols were used to maintain clarity in identifying areas on the map. Unlabeled areas can be identified readily by inspection of the pattern of formations. In order to avoid excessive numbers of colors, units within a particular geologic group bear the same color. In many large areas in which no outcrops occur the soil cover is indicated.

Samples of mineral raw materials were either examined in the laboratories of the Bureau or sent to outside laboratories. Four analyses of coal samples were made in the laboratories of the U. S. Bureau of Mines and nine water analyses were made in the laboratory of the U. S. Geological Survey in Albuquerque. Clay and sand samples were sent to commercial laboratories for evaluation. Geophysicists of the Research and Development Division of the New Mexico Institute of Mining and Technology made measurements in Buell Park in an attempt to delineate the floor of the filled crater.

ANNOTATED BIBLIOGRAPHY

In the course of their studies, the writers had the advantage of the work of other geologists in this area. The following briefly annotated bibliography is restricted mainly to papers on the geology of the Fort Defiance-Tohatchi area, although a few papers on adjacent areas of importance to a discussion of the rocks in this area are included. A complete list of all papers to which reference is made is appended to this volume.

1861. Newberry, J. S., *Geological report,* in Ives, J. C., Report on the Colorado River of the West, explored in 1857 and 1858, pt 3, 91-93. Includes the first brief comment on rocks around Fort Defiance, with geologic strip-map from Oraibi to Fort Defiance.

1875. Gilbert, G. K., *Report on the geology of portions of New Mexico and Arizona examined in 1873,* Rept. U. S. Geog. and Geol. Surveys west of the 100th meridian (Wheeler), pt 3, 559-560. Includes brief description of Black Creek Valley and Defiance anticline.

1875. Howell, E. E., U. S. Geog. and Geol. Surveys west of the 100th meridian (Wheeler), pt 3, 274, 277, 288, and 299. Includes comments on Fort Defiance anticline and coals east of Fort Defiance; also geologic section (fig 121, p 288) extending east from Fort Defiance.

1906. Schrader, F. C., *The Durango-Gallup coal field,* U. S. Geol. Survey Bull. 285, 241-258. Includes an incomplete geologic sketch map covering area.

1907. Shaler, M. **K.,** *A reconnaissance survey of the wesetrn part of the Durango-Gallup coal field of Colorado and New Mexico,* U. S. Geol. Survey Bull. 316, 260-265. Includes the first fairly accurate geologic map covering the area, showing general outline of Chuska sandstone, location of igneous bodies and Jurassic-Cretaceous contacts. One coal outcrop in the area mentioned.

1909. Sterrett, D. B., U. S. Geol. Survey Min. Res., 1908, pt 2, 823-827, 832-835. Includes a detailed description of the occurrence of garnets and peridots in Buell Park and around Fort Defiance. First mention of peridotite in Buell Park.

1910. Darton, N. H., *A reconnaissance of parts of northwestern New Mexico and northern Arizona, U.* S. Geol. Survey Bull. 435, 88 PP. Includes mention of Triassic rocks in Fort Defiance uplift (p 43), Fort Defiance anticline (p 67), a geologic map similar to that of Shaler (1907), and the first structural contour map to include the area.

1912. Gardner, J. H., in Lee, W. T., *Stratigraphy of the coal fields of northern central New Mexico,* Geol. Soc. America Bull., v 23, 571-686. Includes annotated bibliography referring to New Mexico coal and Cretaceous stratigraphy.

1916. Gregory, H. E., *The Navajo country; a geographic and hydro-graphic reconnaissance of parts of Arizona, New Mexico, and Utah,* U. S. Geol. Survey Water Supply Paper 380, 219 pp, 29 pls, 29 figs. Includes excellent geographic descriptions of all the major physiographic divisions of the area, and a description of the surface-water supply and ground-water potentialities.

1917. Gregory, H. E., *Geology of the Navajo country; a reconnaissance of parts of Arizona, New Mexico, and Utah,* U. S. Geol. Survey Prof. Paper 93, 161 pp, 34 pls, 3 figs. The standard work on the geology of the Navajo country, and the best description of the pre-Cretaceous rocks of the area that has been published to date.

1924. Reeside, J. B., Jr., *Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin of Colorado and New Mexico,* U. S. Geol. Survey Prof. Paper 134, 70 pp, 4 pls, 5 figs. Includes first detailed description of the post-Jurassic rocks of the San Juan Basin, lying to the northeast of the area.

1925. Sears, J. D., *Geology and coal resources of the Gallup-Zuni Basin, New Mexico, U.* S. Geol. Survey Bull. 767, 53 pp, 17 pls, 4 figs. Separates the Mesaverde rocks occurring to the south into stratigraphic units applicable within the area.

1927. Reagan, Albert B., *Garnets in the Navajo country,* Am. Mineralogist, v 12, n 11, 414-415. Brief reference to garnets in Buell Park.

1929. Baker, A. A., and Reeside, J. B., Jr., *Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado,* Am. Assoc. Petroleum Geologists Bull., v 13, 1413-1438.

Includes measured sections of Permian rocks at Fort Defiance correlated with other areas in the southwest.

1934. Sears, J. D., *Geology and fuel resources of the southern part of the San Juan Basin, New Mexico: Part 1. The coal field from Gallup eastward toward Mount Taylor, U. S.* Geol. Survey Bull. 860-A, 29 pp, 17 pls.

Further divides and correlates Mesaverde rocks occurring southeast of the area.

1936. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., *Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado,* U. S. Geol. Survey Prof. Paper 183, 66 pp, 33 pls, 16 figs.

Includes correlation (later revised, 1947) of Jurassic section in Todilto Park with other areas in the above western states.

1936. Williams, Howel, *Pliocene volcanoes of the Navajo-Hopi country,* Geol. Soc. America Bull., v 47, 111-172.

Includes description of the occurrence, structure, petrography, petrology, and origin of the igneous rocks of Buell Park, Fluted Rock, Outlet Neck, The Beast, Green Knobs, Zilditloi Mountain, Beelzebub, and dikes in the south part of Todilto Park.

1941. Reiche, Parry, *Erosion stages of the Arizona Plateau as reflected in a headwater drainage area,* Mus. of Northern Ariz., Plateau, v 13, n 4, 53-64.

Includes small-scale geologic map of southeastern part of area, upon which are plotted terrace and pediment remnants of eight ages. Relationships between the different surfaces graphically explained by vertical sections. Excellent geomorphic discussion of area around Mexican Springs.

1941. Sears, J. D., Hunt, C. B., and Hendricks, T. A., *Transgressive and regressive Cretaceous deposits in southern San Juan Basin, New Mexico,* U. S. Geol. Survey Prof. Paper 193-F, 101-121, 7 pls, 5 figs. Elaborates on the intertonguing theory of origin of the Mesaverde rocks in San Juan Basin.

1947. Baker, A. A., Dane, C. H., and Reeside, **J.** B., Jr., *Revised correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico and Colorado,* Am. Assoc. Petroleum Geologists Bull., v 31, n 9, 1664-1668.

Brief description of revised correlations affecting Jurassic rocks in Todilto Park and elsewhere in the area.

1947. Pike, W. S., Jr., *Intertonguing marine and nonmarine Upper Cretaceous deposits of New Mexico, Arizona and southwestern Colorado,* Geol. Soc. America Mem. 24, 103 pp, 12 pls, 7 figs. Includes four measured stratigraphic sections of Cretaceous rocks in the area, and correlates them with sections to the north and south. Lists fossils from localities in the area.

1949. Halpenny, L. C., Brown, S. C., and Hem, J. D., *Water-supply investigation of Fort Defiance area, Navajo Indian Reservation, Apache County, Arizona,* U. S. Geol. Survey, Ground Water Branch, Holbrook, Arizona, mimeographed circular, 11 pp, 2 pls.

Brief report on local water resources.

1950. New Mexico Geological Society, *Guidebook of the San Juan Basin, New Mexico and Colorado, First Field Conference,* 153 pp. 38 figs.

Includes articles on geologic history of the San Juan Basin (Beaumont and Read, pp 49-52), map of Precambrian rocks showing Quartzite Canyon locality (Kelley, p 55), isopachous map of Pennsylvanian rocks (Bradish and Mills, p 59), comments on Permian rocks of Defiance uplift (Read, pp 62-66), Triassic rocks with isopachous map (Wengerd, pp 67-73), Jurassic rocks (Hoover, p 76-81), regional structure and tectonic evolution (Kelley, pp 101-108).

1951. Halpenny, L. C., *Preliminary report on the ground water resources of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah,* U. S. Geol. Survey, Ground Water Branch, Holbrook, Arizona, mimeographed circular, 13 pp, 1 pl. Brief discussion of geologic formations, their water-bearing properties, the major structural features and their relation to water supplies, and the principal aquifers of the region.

1951. Harshbarger, J. W., Repenning, C. A., and Jackson, R. L., *Jurassic stratigraphy of the Navajo country,* U. S. Geol. Survey, Ground Water Branch, Holbrook, Arizona, mimeographed circular, 8 pp, 3 pls.

Includes brief review of Jurassic formations and sets up the Cow Springs sandstone unit, which appears in the Fort DefianceTohatchi area.

1951. Leopold, L. B., and Snyder, C. T., *Alluvial fills near Gallup, New Mexico,* U. S. Geol. Survey Water Supply Paper 1110-A, 19 pp. Includes description and sketch of type locality of Nakaibito formation near Mexican Springs.

1951. New Mexico Geological Society, *Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona, Second Field Conference,* 163 pp, 48 figs.

Includes road log through the area from Fort Defiance to Todilto Park, pp 66-73 (mile 56.5 to 80.7), mentions Permian rocks of Defiance uplift (Read, pp 80-81), Triassic rocks (McKee, p 88), Jurassic rocks (Harshbarger, Repenning, and Jackson, pp 96-98), Cretaceous rocks (Silver, pp 108-115), igneous rocks (Callaghan, p 120), tectonics (Kelley, pp 124-131), gem stones around Fort Defiance and in Buell Park (Bieberman, p 142).

1951. Wright, H. E., Jr., and Becker, R. M., *Correlation of Jurassic formations along Defiance monocline, Arizona-New Mexico,* Am. Assoc. Petroleum Geologists Bull., v 35, 607-623.

Includes short description and correlation chart of Jurassic units, and two measured sections in the area.

1951. Wright, H. E., Jr., (abs) *Opal cement in thick Tertiary eolian sandstone, Chuska Mountains, Arizona-New Mexico,* Geol. Soc. America Bull., v 62, 1492.

Briefly describes the physical characteristics of the Chuska sandstone.

ACKNOWLEDGMENTS

The writers, as citizens of New Mexico, are grateful for the opportunity to be of service to another group of citizens, the Navajos, many of whom reside in this State. It is a pleasure to acknowledge help and encouragement from Mr. Sam Ahkeah, Chairman of the Tribal Council, as well as from other officials of the Tribe, particularly Mr. K. N. Gerard, Tribal mining engineer. Many Navajos provided helpful information in the field. All officials and employees of the Bureau of Indian Affairs who were contacted were uniformly helpful, but the writers are especially grateful to Mr. Russell Fister, Director of Natural Resources, who was the official immediately concerned with the negotiation and administration of this contract and who provided many courtesies which facilitated the work.

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The writers are indebted to their associates mentioned elsewhere in this report who have contributed so much knowledge and effort to the project, and to other members of the staff who participated in the field work, including Brewster Baldwin, John Schilling, Wayne Bundy, Willow Burand, and John Hill.

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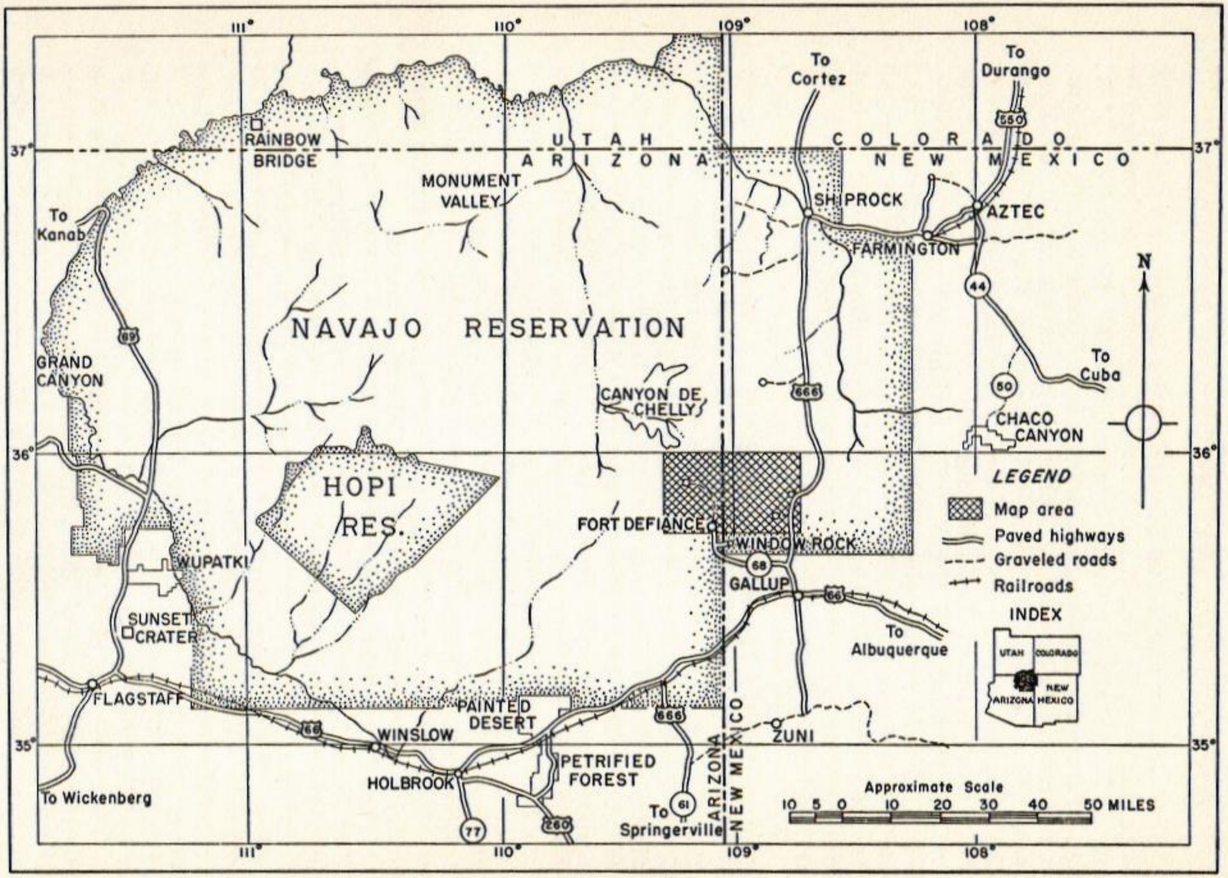
Other agencies, particularly the U.S. Geological Survey and the U. S. Bureau of Mines, aided with geologic or economic data. The writers wish especially to acknowledge the fruitful conferences with John Harshbarger of the Ground Water Branch of the Survey, and with C. B. Read and E. C. Beaumont of the Fuels Branch. The various companies and individuals who helped with tests, samples, and data are given acknowledgment in the text.

Figure 1



Index map showing location of Fort Defiance and Tohatchi quadrangles in the Navajo Indian Reservation.

GEOGRAPHIC AND CULTURAL FEATURES

Fort Defiance and Tohatchi quadrangles include an area of 483.6 square miles wholly within the Navajo Reservation and bounded by parallels 35° 45' and 36° N. and by meridians 108° 45' and 109° 15' W. (fig 1). Part of Fort Defiance quadrangle is in Apache County, Arizona, but the remainder and all of Tohatchi quadrangle are in McKinley County, New Mexico. The principal community, Fort Defiance, is 35 miles by paved road northwest of Gallup, the largest nearby city, and 6 miles from Window Rock, the administrative headquarters for the Navajo Reservation. U. S. Highway 666 is within or near the east boundary of Tohatchi quadrangle. Aside from this and the graveled road from Fort Defiance to Sawmill and a few additional short stretches, all roads are unsurfaced. Most of those reaching Indian hogans in the back country are scarcely more than trails, which for the most part can be travelled best by jeep or pickup.

The Fort Defiance-Tohatchi area is dominated by the flat-topped plateau of Chuska Mountain (figs 18 and 19) which has an average altitude of more than 9,000 feet and is the highest area within the Reservation. To the east is the broad open valley of the Chaco River, the "Chuska Valley" of Gregory; tributary to the Chaco are the washes draining much of Tohatchi quadrangle (fig 5). The western part of the area is dominated by the broad topographic dome of the Defiance uplift whose crest has an average altitude of 7,500 feet. Black Creek Valley, which has a minimum altitude of 6,700 feet, lies along the east side of the Defiance uplift. The east side of the valley is marked by colorful sandstone cliffs which rise to the dissected upland of the Manuelito Plateau (fig 12, pl 4-A). The east side of the valley is interrupted by a subsidiary valley, Todilto Park, which is almost wholly surrounded by sandstone cliffs (pls 2 and 3). The whole area has a mountainous aspect unusual for the broad expanse of the Colorado Plateau.

The relatively flat summit of Chuska Mountain is dimpled by some 130 undrained depressions which under favorable conditions may contain lakes or ponds. Otherwise, the region is well drained by intermittent streams. The only permanent streams are the upper reaches of the Todilto, Bowl Canyon, and Red Willow washes which are fed by springs along the west side of Chuska Mountain. Flash floods from summer thunderstorms may be expected from June to September. Melting snow or rain may provide smaller intermittent flows in winter and spring. The alluviated valleys are commonly trenched deeply by gullies which, if not restricted, cut back to remove the accumulated soil.

Tabulated data on climate are appended to this volume. In view of the range in altitude of 3,000 feet, considerable variations in temperature and precipitation from place to place can be expected. In general, the average January temperature may be said to range from 25° to 30°F and the July temperature from 65° to 75°F. The average annual precipitation is between 10 and 13 inches, of which more than half falls between April and September. The first killing frosts generally come between September 30 and October 20 and the last between May 1 and May 30.

Except for the lower parts of Tohatchi quadrangle in the Chaco drainage, the whole area is green when viewed from a distance. Aside from the lower areas covered by piñon and juniper, there is a considerable stand of merchantable timber, mainly ponderosa pine, which is being harvested through the Tribal enterprise at Sawmill. Owing to the range in altitude, several plantlife zones are represented. A list of 351 plant species found in the Navajo Reservation is appended to this volume through the courtesy of Percy E. Mellis, Forester for the Window Rock Area, and Don W. Clark, Range Conservationist.

The following plantlife zones are represented:

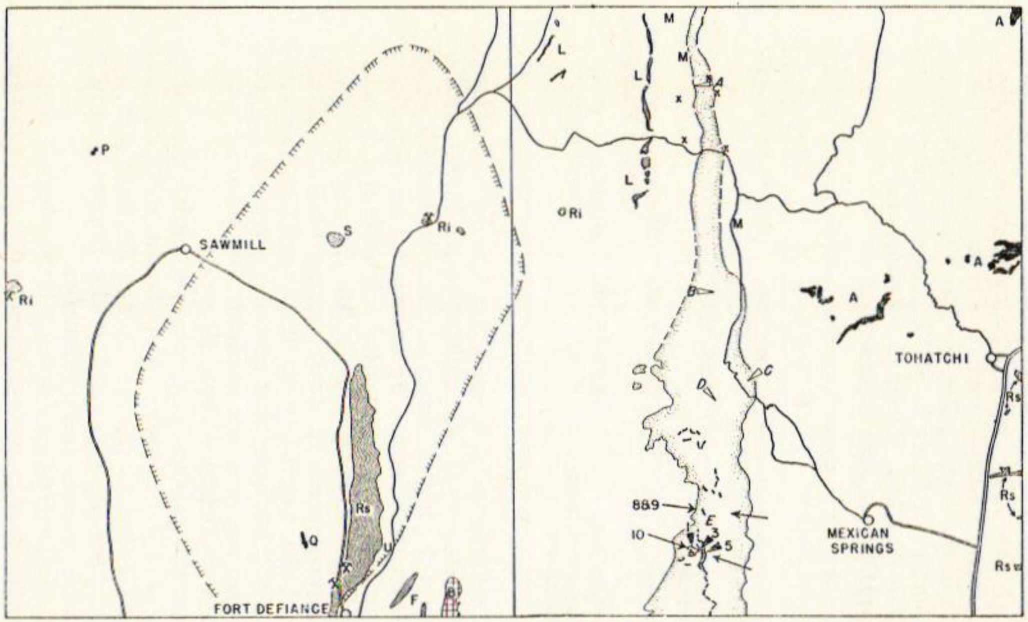
ZONE	CHARACTERISTIC PLANTS	ELEVATION (ft.)	LOCATION
Hudsonian	Alpine fir, Engelmann spruce, and corkbark fir	9,000-12,000	Chuska Mountain?
Canadian	Douglas fir, white fir, blue spruce, and aspen	8,000- 9,000	Chuska Mountain
Transition	Ponderosa pine	7,000- 8,500	Manuelito and Defiance Plateaus
Upper Sonoran	Piiion, juniper, oak, sagebrush, sacaton, blue grama, and galleta	4,000- 7,500	Chuska and Black Creek Valleys

To this variable, yet inhospitable, land the Navajo has adjusted himself with remarkable success. He depends upon his herds of sheep and goats which graze on the higher slopes in summer, but which are brought to lower levels for the winter. The uncertainty of rainfall and the lack of water for irrigation has prevented any extensive farming; even at the present time scarcely 500 acres within the area are under regular cultivation. Improvements in water storage both on Chuska Mountain and at Red Lake, together with other works, are expected to provide a total of nerly 3,000 acres that reasonably may be expected to be cultivated. An exact census is not available, but probably about 500 Navajos live in the Fort Defiance-Tohatchi area.

Superimposed upon this pastoral pattern of the native population are the communities of Fort Defiance (population 619), Mexican Springs (about 50), and Tohatchi (about 75). For the most part, this population group represents the personnel of the Bureau of Indian Affairs together with a few traders and missionaries.

The Tribal lumbering enterprise at Sawmill is the cause of another population center, peopled in this instance almost entirely by Navajos. Between 1936, the year of its beginning, and the end of 1952, this enterprise has logged 137,780,000 board feet of timber from 38,077 acres of land. The cut at the mill in 1952 was 15,142,310 board feet. The total stand of timber has been estimated to be 548,899,000 board feet, of which all but 1.8 percent is ponderosa or yellow pine.

Beyond some quarries for road metal, there is no mineral production from this area.



NONMETALS

A Bentonitic shales
B Building stone (accessible)
F Flagstone (accessible)
L Limestone (accessible)
P Pigment (hematite)
Q Quartzite
Ri Road metal (igneous)
Rs Road metal (sedimentary)
— Road metal (baked shale)
S Semi-precious stones
Area in which scattered semi-precious stones occur

COAL

Outcrop trace of coal bed
Measured coal bed
Sampled coal bed
x Outcrop of thin coal bed
Area in which potentially economic coals crop out
Measured coal sections

METALS

M Manganese concretions
U Radioactive locality
Paved highway
All-weather road
Fair-weather road
Quarry

Figure 2

INDEX MAP SHOWING LOCATION OF MINERAL DEPOSITS IN FORT DEFIANCE AND TOHATCHI QUADRANGLES.

Mineral Resources and Ground Water

SUMMARY

Briefly, the known mineral resources of the Fort Defiance-Tohatchi areas are shown on the map (fig 2) and summarized herewith.

METALS

Nodules of manganese oxides are distributed sporadically along the base of the Chuska sandstone. No occurrence of commercial importance was found and none is expected.

As yet no minable deposit of uranium-bearing minerals has been found, though formations which both to the north and southeast are major sources of uranium are widely distributed in the area. Prospecting with Geiger counter or scintillometer has revealed only slight shows, but radiometric prospecting will no doubt be continued and a workable deposit may yet be found.

NONMETALS AND INDUSTRIAL MATERIALS

Clays derived from the weathering of shales and other rocks are widely distributed in the area. Such tests as have been made show that these are low-fusion or impure clays consisting largely of the mineral montmorillonite. They must be blended with higher-grade clays for ceramic use. The clay-material bentonite, consisting largely of the mineral montmorillonite, occurs in large quantities in the Tohatchi formation as well as in the Chinle formation and possibly elsewhere in the geologic section. The usefulness of this material, particularly as a mud for oil test drilling, depends on its physical characteristic of swelling when placed in water. Tests made thus far of material from the Tohatchi formation show that it falls short of meeting specifications for drilling mud. Adequate deposits may yet be found with further prospecting and testing.

Sands derived from the abundant sandstones are widespread, and some of the sandstones are leached of some of their inherent impurities. The long distance to any point of consumption precludes the use of these sands for foundry purposes. Tests made for glass sand, which conceivably might be used in a local industry, thus far have been disappointing both as to size distribution and impurities. Possibly bottle glass could be produced.

Sandstones that could be used for building are widely distributed. The Entrada sandstone has been utilized very effectively for many structures at Window Rock. Undoubtedly, some stone could be found which would have ornamental value. Some of the sandstones could be used for flagstones. The quartzite would be particularly durable for this purpose, but there is a question whether it can be split into slabs of convenient sizes.

Ready sources of high-silica gravel are essentially lacking, except where the Shinarump conglomerate is weathered sufficiently to be excavated. Debris produced by the weathering of igneous rocks has been used, as has shale baked by the burning of coal beds. The hard phases of the igneous rocks could be crushed and sized for construction purposes.

Olivine, or peridot, and the pyrope variety of garnet occur in soil derived from some of the igneous bodies. These occur mostly as small grains which probably could be mounted in attractive forms and marketed. Petrified wood occurs in considerable quantities and possibly could be prepared in attractive forms for marketing.

MINERAL FUELS

Coal beds of commercial size and grade occur in Tohatchi quadrangle in amounts adequate for any local industry that might be established.

No oil or gas has been discovered, but the thick sedimentary section in Tohatchi quadrangle and the possibilities of traps therein are encouraging to future exploration.

GROUND WATER

The Chuska sandstone is the source of considerable spring water, and the sandstones in the Cretaceous formations are potential sources, as yet only slightly explored, for ground water. The valley fill alluvium is of local importance only and mostly yields water of poor quality.

RECOMMENDATIONS

As to specific recommendations concerning mineral resources, each mineral raw material is a special problem. In spite of the marked increase in population of New Mexico and Arizona, these regions offer little market for the materials that could be produced in bulk in the Fort Defiance-Tohatchi area. If the initial tests of the bentonitic shales had proved satisfactory, a ready market might have been developed in San Juan Basin. It is recommended that these shales continue to be investigated. Sandstones of adequate durability that have especially desirable characteristics of color variation or form can be shipped. These possibilities should be investigated thoroughly. Coal obviously is available for any local industry. Coal in this area should be considered in the light of possible new uses as a source of chemicals as well as of energy. Coal that could be mined cheaply by stripping is especially attractive. The search for petroleum and natural gas should be encouraged. The establishment of local industries will be controlled to a considerable extent by the available water supply. More deep wells will be needed to explore the ultimate possibilities of water supply.

The writers are encouraged by the unique status of the people, as well as by the characteristics of the region, to make suggestions as to two possible income sources that might be exploited: scenic attractions and ornamental stones.

Experience shows that Americans are willing to spend money in order to visit scenically interesting regions. A veritable stream of tourists passes the Reservation annually between Gallup and Flagstaff. Along the highway, signs remind them that they are in "Indian country," and they see, indeed, a great many roadside stands in front of which rows of trinkets are displayed by an Indian. Examination of these objects shows that about half of them are identical with cheap novelties and crockery that can be seen on similar stands in the Ozarks, Illinois, New York, and countless other places.

In our opinion, the artificial and unnecessary remoteness of the Reservation can be broken, with a resulting handsome profit for the Tribe, if at places such as Gallup a well-advertised and neatly-appointed parking area by the main highway were to inform travelers that they could interrupt their cross-country drive at that point with an interesting circuit drive through the Navajo-Hopi Reservation. For such a purpose, a bus in good repair is waiting, with a driver who speaks English fluently and knows the region equally as well as his motor. American tourists who visit Yellowstone National Park, Glacier National Park, or many National Monuments, find precisely these convenient and inviting accommodations waiting for them; schedules, personnel, and travel facilities are excellently organized and, as many annual reports of the National Parks Service prove, such tours have not only been of great educational advantage to the American people, but also a source of revenue to the U. S. Treasury. It seems certain beyond reasonable doubt that tours as here envisaged—under Navajo guidance, through Reservation terrane, with varied and distinctive scenery at every mile—will be a financial success. Even with our limited acquaintance with the Reservation, we can make two suggestions for such tours:

I. *A one-day tour, from Gallup via Window Rock and Sawmill to Canyon De Chelly, and return via Ganado.* To make this tour a success, the 20-mile stretch of dirt road between Sawmill and the southern entrance of Canyon De Chelly should be improved, so that it can be regarded as an all-weather road. Fortunately, very good road metal is available at the quarry site on the southern slope of Fluted Rock, near this road. This route would show visitors the new buildings at Window Rock; also, the general plan and organization of the Tribal Council and its functions could be explained en route. Next, the tourists would see Navajo hogans, which are not visible on U.S. Highway 66; they would pass through Fort Defiance and see two old trading posts and the hospital. The road then would take them past the sawmill, and the practice of lumbering the huge ponderosa forest could be outlined. As they continued to Canyon De Chelly, the scenery of the pine-covered plateau would make its impression. Canyon De Chelly is relatively little seen by tourists. The southern entrance, where the walls are 900 feet high, is as impressive as parts of Zion National Park, or Yosemite Valley. As the tour arrives at the National Monument headquarters, the party should find modern and adequate facilities for rest and good meals at reasonable rates. The return trip, via Ganado, would familiarize the participants with the Chinle plains, red, gray, brown, arid, and barren—yet inhabited by Navajos. It is hard to imagine a person who would not be profoundly impressed with the stamina of a race that has accomplished the incredible, and survives in a region as devoid of all amenities of life as the Chinle Plateau. And to find, at the fairground near St. Michaels, an art exhibit as comprehensive and unique as the displays of the Art Guild, should make a lasting impression on the visitor of the accomplishments of this remarkable Indian tribe. The fare for this trip should be reasonable, and both at Canyon De Chelly and at the fairground the passengers should find ample opportunity to purchase Indian craft objects, rugs, pottery, good paintings, and so forth.

2. *A similar, but shorter, round-trip could well be organized to go from Gallup to Window Rock, St. Michaels, and back.*

It goes without saying that tours as here outlined may not be a financial success at the start. The financing presumably could be underwritten for a few years by arrangements between the Tribal Council and the Indian Service. It is most important that better ways and means be found to acquaint the American people on the whole with the problems of the Navajo and Hopi tribes. An informed public opinion is a desideratum. Tours like those here suggested may prove a very efficient method of achieving this end. Once the road from Sawmill to Canyon De Chelly has been improved, conducted tours may not be needed, but the availability of a good road net should be properly advertised to the public and accommodations should be held at a level commensurate with the requirements of modern American travelers. Quite possibly, the vicinity of Gallup might not serve as a feasible or desirable starting point for informative tours as here pictured. This is probably of secondary importance. The chief points are that the Navajo and Hopi tribes are believed to be in a position to obtain revenue from the scenery of their land, and that better contacts between Whites and Indians are possible. It might be desirable to provide tourists with nontechnical literature dealing with the Reservation, the scenery, and the points of special interest on their drive, as is usually done in National Parks. Such pamphlets could be illustrated with black-and-white pen and ink sketches at nominal cost.

The second potential source of income lies, we believe, in the availability of certain ornamental stones. To turn these into money, the Navajos must be made familiar with the stones themselves, their uses for the white man must be explained, and ways and means must be found to stimulate the inherited artistic skill of the Navajos, so that these new stones can be added to the turquoise and silver with which the Tribe has won world renown.

New state and federal projects are bringing many families into the vicinity who can afford to live in comfortable homes, and thousands of new homes are being built in the large area surrounding the Navajo and Hopi Reservation. Modern homes are designed with good taste and attract many retired couples who come from northern and eastern states to escape the severe winters. Increasing trade and new industries attract additional thousands to the Rocky Mountain area surrounding the Reservation. This stimulates the building industry and develops new markets for building materials. The Reservation has stones that compare favorably with materials procured from other areas. As an example, the middle portion of the Chinle formation has many zones of pale-maroon to salmon-colored, fine-grained sandstone that flake into slabs 1 to 4 inches thick, and several square feet wide. Such material could be put to good use as flagstone in gardens, retaining walls, and in the walls of homes; the slabs could be used for sidewalks, pavements in garden walks, in mantelpieces, and in walls surrounding chimneys and fireplaces. Public buildings, churches, facades of business offices, restaurants, and gasoline stations could be embellished materially by the use of these flagstones. They are easily obtainable in quantity. Enough to fill hundreds of trucks could be obtained in Black Creek Valley, east and northeast of Fort Defiance, and in other places located closer to all-weather routes outside the area surveyed. The innumerable motels and tourist courts that have sprung up along U. S. Highway 66 no doubt would be seriously interested in buying this very handsome ornamental stone to add to the attractiveness of their buildings. This flagstone is easily obtainable. All that is needed is a truck, a crowbar, and a display and storage place where customers can inspect the goods. To establish a trade in such a commodity requires a little enterprise, organization and skill, and good publicity.

We are convinced that the Tribe could turn the immense volume of silicified wood into a profitable business with the aid of a few artists, craft specialists, and clever salesmen. At present, petrified wood—nearly all of red color—can be seen in displays of jewelers, or crafts. Silica is very hard, and the polishing makes it expensive. But there are other petrified woods—black, gray, tan, or mottled colors—in quantities 10 or 100 times the volume of the red wood, lying idle in countless ravines, on hill slopes, and plateaus.

A modern 16-in. diamond saw will cut blocks of silicified wood, as large as 7 x 10 in., in 20 minutes or less. The cut surface is so smooth and so free from irregularities that a coat of krylon will give it a luster indistinguishable from a good polish. If the surface wears off, it can be renewed in a few seconds by means of another spray. With such a saw, a block of silicified wood can be slabbed into a dozen or more nearly identical pieces within a few hours. The cut can be made across the grain, or parallel to it. In the first case, the surface gives patterns of arcs and lenses and even complete circles, if the piece is a complete cross-section of a trunk. Slabs cut parallel to the grain show innumerable parallel lines. Such slabs, set parallel with each other, can be arranged into ornamental designs resembling inlay tiles or mosaics, with a very great variety of possibilities in pattern. A resourceful interior decorator could without difficulty find dozens of uses for such plates of "offcolor" petrified wood. In fact, the subdued grays and tans make wood of this shade particularly desirable where conservative hues are wanted, or where rooms and walls are designed in pastel shades—so popular nowadays in modern construction.

Much of this wood is translucent in thin plates. On a diamond saw, plates only 1 mm thick can be cut without trouble. Holes can be drilled into the material, and all kinds of handsome objects can be fashioned: lamp shades, window screens and drapes made of parallel vertical rows of thin strips, transparencies for hanging in windows, Christmas decorations, pins, brooches, mosaics in imitation glass for placing in front of neon or ordinary bulbs to provide indirect lighting, and so on. Thick, opaque plates can be arranged in a great variety of designs and mosaics to decorate walls and floors in lobbies and homes, to frame doors and windows, or to break the monotony of large plain walls—much as is done with oddly shaped bricks in modern masonry. The beauty and value of Indian pottery, in our opinion, would be enhanced by embedding mosaics of thin, sliced wood in wares of traditional design. Trays, plant tiles, flowerpots, perfume kits, decorative bricks, bowls, and dishes could be so ornamented. Granted, such merchandise would not symbolize the tribal traditions. But it would be work by Navajos, and the designs formerly wrought into rugs, blankets, and sand paintings could well come to life in yet another form of expression.

To expand a market for petrified wood, and make the "offcolor" shades more popular, display rooms again would be desirable. We imagine that established craft centers, such as at the fairground, would welcome the innovations and would be hospitable and helpful to Navajos who bring in material of good quality. Many truckloads of nearly white petrified wood, in large and small blocks, can be secured along the valley that extends northeastward, 2 to 4 miles northwest of Buell Park. Gray and mottled wood is available in quantity in the large meadow north of Fluted Rock, and on the hillside a quarter of a mile southwest of the Rock. Red, yellow, and brown shades can be collected in many ravines west of the Fort Defiance-Red Lake road, about 1 to 2 miles north-northeast of Fort Defiance. Many other areas in the mapped quadrangles are rich in this potentially valuable material.

METALS

MANGANESE

Nodular concentrations and impregnations of manganese oxides have been found at a number of places just above the nearly horizontal unconformity between the Chuska sandstone and underlying formations (fig 2). Aggregates of manganese concretions of pisolitic size, cementing the sandstone, increase in abundance northward along the west side of Chuska Mountain. Frequently the obscured contact may be inferred from resistant boulders of this material.

The manganese probably had its origin in the solution by meteoric waters of minute amounts disseminated throughout the considerable thickness of Chuska sandstone. These particles were concentrated at the base of the unit during reprecipitation, particularly in localities where the Chuska overlies such relatively impermeable units as Mancos shale or Recapture shale.

It is doubtful if concentrations occur along the east side of Chuska Plateau, where the contact is obscured by landslides along most of its length. The unconformity has a gentle westward dip which resulted in westward migration of the mineralizing waters—much as ground water flows today.

No manganese concentrations of potential economic importance have been observed in the mapped area.

RADIOACTIVE MATERIALS

No deposit of uranium or other radioactive metal was found in the Fort Defiance-Tohatchi area, though rock belonging to the Chinle formation in a road-cut 4 miles north of Fort Defiance (fig 2) was found by C. R. Maise, of the Atomic Energy Commission, to show some effects on the Geiger counter. Radiometric prospecting doubtless will be continued and a workable deposit may yet be found.

It should be pointed out that many of the formations in the Fort Defiance-Tohatchi area are correlative, or coextensive with, formations which elsewhere in the Colorado Plateau contain radioactive deposits of economic importance. Such a deposit occurs in the Morrison formation 30 miles north of this area and in the Dakota (?) sandstone 15 miles south of the area. All of the six rock units—Shinarump conglomerate, Chinle formation, Todilto limestone, Morrison formation, Dakota (?) sandstone, and Mesaverde group—which elsewhere have yielded workable uranium deposits, occur in this area and underlie about 80 percent of its surface. Therefore, the entire area must be considered as favorable to prospecting.

Almost everyone is familiar with the Geiger counter as a field instrument for detecting radioactivity. Radioactivity in itself does not necessarily indicate a workable deposit of uranium, but any area of positive reaction should be investigated. Directions for prospecting are contained in a booklet available from the Office of Technical Services, Department of Commerce, Washington 25, D.C., called *Prospecting with a Counter* (1953), by Robert J. Wright. Also useful to the inexperienced prospector is the publication *Prospecting for Uranium* (1951), published by the Atomic Energy Commission and available from the Superintendent of Documents, Washington 25, D.C. Other important reports are those by Rheinhart,[1] Weir,[2] and Love.[3]

Aside from radioactivity which may be detected by the Geiger counter, or by the much more sensitive scintillometer, the following characteristics should be considered by the prospector:

1. Uranium minerals appear as brightly colored (yellow, and to less extent, green) specks of secondary minerals in sandstone and limestone.

2. Ores are commonly associated with deposits of woody material or coal.

3. All ores that have been located in the Shinarump lie at or very near the base of the formation.

4. Ores in the Chinle are commonly associated with zones where the varicolored shales have been bleached to olive-green, or where yellow limonite mineralization has taken place.

1. Reinhart, E. V. (1952), *Practical guides to* uranium *ores on the Colorado Plateau, Atomic* Energy Commission RMO-1027.

2. Weir, Doris Blackman (1952), *Geologic guides to prospecting for carnotite deposits on the Colorado Plateau,* U.S. Geological Survey Bull. 988-B.

3. Love, **J. D.** (1952), *Preliminary report on* uranium *deposits in the Pumpkin Buttes area, Powder River Basin, Wyoming,* U.S. Geological Survey Circ. 176.

5. Ores in pink or red Morrison sandstone also are associated with bleaching to yellow-gray or gray-green.

NONMETALS AND INDUSTRIAL MATERIALS

CLAY

The term "day" is applied usually to certain fine-grained earthy rocks whose most prominent property is that of plasticity when wet (AIME, 1949, p 207). Clay may be composed of one or more of several minerals, generally hydrous aluminum silicates. Its physical characteristics, which make it of use in a multitude of capacities, generally depend upon the type of mineral and the degree of purity.

Clay is found throughout the geologic section in the area, being particularly abundant in the Chinle formation, the Recapture shale, the Mancos shale, and in the Crevasse Canyon, Menefee, and Tohatchi formations. For the most part, however, these clays contain impurities such as sand and silt, iron oxides, and carbonaceous material which prevent them from being of immediate economic importance. A few deposits are of sufficient purity to justify sampling and testing for various uses.

The chief use of clay is in the ceramic industry, where different types of days may be used in the manufacture of refractory brick, china, earthenware, porcelain, stoneware, brick, tile sewer pipe, and other specialized products. Several samples were taken from beds associated with the coals in the Crevasse Canyon and Menefee formations and submitted for ceramic analysis to Mr. Roger Sherman of the Navajo Ceramic Products plant at Gamerco. It was found that the clays contained montmorillonite, which caused them to crack on drying, and prevented their use except as admixtures tourer days. One sample, taken from an alluvial deposit in the bed of Catron Creek, was found to be an excellent pottery clay. This deposit is small and can be mined only during parts of the year, although several tons of material can be collected from time to time as conditions permit.

Bentonite, a sedimentary clay in which the mineral montmorillonite is an important constituent, has the property of swelling and increasing many times in volume when wet, and—conversely—of shrinking and cracking when dried. This and other properties make it useful as a bonding agent in synthetic foundry sands, and as a filter, absorbent, bleach, and gel-former. It also is used in polishes, water-paints, adhesives, asphalt emulsions, and in a variety of other products. Quantitatively, its largest single use today is as a mud in the drilling of oil wells (Stern, 1941). A number of samples taken of the days in the upper part of the Tohatchi formation were submitted to several organizations which might be interested in developing them for use in the extensive drilling program now underway in San Juan Basin. Returns obtained to date are not favorable, but tests are being continued. Bentonitic days also are found in the Chinle, particularly near the top of the section, and in the Recapture shale. It is possible that pure beds may be found in these formations, but such were not observed by members of the survey.

SAND

Special sands are those used for a multitude of particular purposes other than as a concrete and road-building, or construction, aggregate. Among these are foundry sand, glass sand, filter sand, abrasive sand, and furnace sand. These are mostly low-cost products, depending upon nearness to market and low production cost for value. The lack of a local steel industry thus prevents utilization of sand for several of the above uses.

It was conceived that there might be a possibility of finding sand that would permit a small Indian glass industry, producing articles similar to the green glass objects now imported from Mexico. Such quality glass requires sand with chemical analyses of more than 95 percent $Si0_2$, less than 4 percent $A1_20_3$, less than 0.3 percent Fe_20_8, and less than 0.5 percent combined CaO and MgO (AIME, 1949, p 973). Sorting of an ideal glass sand should be essentially minus 20 mesh and plus 100 mesh, with approximately the following distribution on the intermediate screens:

Plus 30 mesh	**1%**	Plus 60 mesh	25%
Plus 40 mesh	5%	Plus 80 mesh	25%
Plus 50 mesh	35%	Plus 100 mesh	9%

One sand sample from the east side of Chuska Mountain gave the following size distribution:

Plus 30 mesh	0.2%	Plus 100 mesh	31.2%
Plus 40 mesh	1.3%	Plus 140 mesh	28.1%
Plus 50 mesh	5.5%	Plus 200 mesh	13.7%
Plus 70 mesh	16.4%	Plus 270 mesh	2.1%
		Through	1.6%

It can be seen that this sand is too fine-grained for an ideal glass sand. It also contains 0.88 percent Fe_20_3, which is nearly three times the allowed amount.

BUILDING AND ORNAMENTAL STONE

Sandstone, of tan, orange, brick-red, or darker shades, is exceedingly common in the area examined but, as with other mineral commodities, a careful appraisal must be made of the demand, the cost of processing, and the qualities of the material before a decision can be reached whether or not rocks from this particular area have commercial possibilities.

So far, the demand for sandstone for building purposes in the immediate vicinity seems to have been small. Local stones have been used in the new buildings at Window Rock, Tohatchi, Mexican Springs, and Fort Defiance, and although they have not yet been exposed to wind and weather for many years, the stone appears to stand up well. Should the demand for building stone increase in the near future, it certainly can be met from local sources. The Entrada formation in particular displays large, natural exposures of a homogeneous, relatively fine-grained sandstone of uniform and pleasing color. It is close to several fair-weather roads and seems to be one of the most satisfactory stones for building construction.

Should a more ambitious program be contemplated, one designed to produce larger quantities of sandstone for use in outlying districts, competition with other areas would have to be considered. Presumably, only ledges near the few all-weather truck roads would be in a sufficiently favorable position to be worked, and the mileage to the nearest railroad would be an important factor. Furthermore, as in all large-scale quarrying operations, there would have to be assurance that the rock was of uniform quality. This is an important factor in the area investigated, because the rock at the outcrop is commonly leached, whereas at greater depth it is unleached. This may have an adverse effect upon the quarrying properties and specifications. Commonly, for example, the sandstones in the Triassic and Jurassic systems have a carbonate cement which has been dissolved to a large extent near the present surface. Though it is true that all carbonate cement is liable to be dissolved in time, the value of a rock as a building stone need not be impaired thereby, because few buildings are intended to remain entirely intact for more than a century. In other words, the deterioration of a rock through exposure to the weather is usually a slow process compared with the length of time that a building stone is expected to remain in a building. Nevertheless, if larger operations are contemplated it would be desirable to examine the microscopic composition of the rock fairly critically. The nature of the cement is of importance, also the percentage of feldspar in sandstone, as well as the degree to which this mineral has been converted to clay minerals.

A few comments may illustrate some of the special properties of the local sandstone formations in regard to their suitability for building purposes.

Precambrian (?) quartzite (fig 2)

The mechanical properties of this rock are excellent. It is by far the most durable in the entire region. For the same reason, however, the removal of blocks and plates from the ledge would be difficult and expensive. The fair-weather truck road, which at present reaches the southernmost outcrop at Bonito Creek, could be improved at little cost to serve as an all-weather road, but drilling and blasting will be necessary to produce larger quantities of the rock. It should be stated, however, that the volume of loose debris at the base of the steep canyon cliffs is so large that for years to come quartzite talus could be used as rip-rap, foundation stone, and for similar heavy construction. On a small scale, the quartzite could be marketed as flagstone. The rock splits parallel to the bedding with sufficient ease that with crowbars and chisels a fair amount of thin slabs could be secured. Very large slabs, however, would be difficult to procure, because closely spaced joints traverse this rock in many directions. Nevertheless, the quartzite is such a strong rock that its durability counterbalances, to some extent, its inherently greater production costs.

 Cutler formation

The lower, brick-red portion of this formation is unsuitable. The rock flakes badly along millions of silt partings, and is one of the least durable in the entire region. The upper, massive-weathering Cutler sandstone has somewhat better qualities, but almost the only outcrop that is reasonably close to a truck road is north of Bonito Canyon. Here the rock is overlain by the vertical cliff of the De Chelly sandstone; consequently it cannot be removed to any depth without causing the collapse of an immense column of rock.

De Chelly sandstone

The pale brick-red to tan sandstone is of uniform grain size, and stands up under the weather fairly well, even where much of the cement has been leached. This rock, however, has crosslamination on such a large scale that much experimentation will be necessary to determine whether facing stone, or larger slabs, can be obtained parallel to the flat-lying true bedding of the rock, or whether larger blocks break so easily along the crosslamination planes that plates must be secured parallel to these. The rock is easily obtainable west and southwest of Sawmill, also directly west of Fort Defiance. But the crosslamination will be a problem in any outcrop.

Shinarump formation

This rock varies its composition, cement, and grain size so erratically that it is not suitable for building purposes. Completely silicified blocks, replete with chert pebbles in many colors, could be sold as ornamental "puddingstone." But cutting and polishing of this rock costs as much as the processing of fossil wood, and the material occurs in such small masses that it seems impossible to establish a steady market for it.

Chinle formation

Several gray or brick-red to pale-maroon, fine-grained sandstone lenses in the lower part of this formation break easily into large slabs, 2 to 5 inches thick. They could well be sold as flagstone in towns like Gallup, as garden facing, sidewalk plates, and for other ornamental purposes. Outcrops of these rocks are numerous along the road leading north from Fort Defiance to Red Lake. One member of the formation, near the top of the sequence, is a rock of particular strength. This is a pale-green, very fine-grained bed of a mildly silicified pellet-conglomerate, about 3 inches thick (fig 2). This rock would stand up very well in heavy masonry, abutments, and dams. It is easily identified, since it forms a low east-dipping ridge on the east side of Black Creek Valley, and is the foundation rock of the spillway a few hundred feet east-southeast of Red Lake. The rock accompanies the road northward from the southeast corner of Red Lake to Green Knobs, and is prominently exposed in the plateau northwest of the point where the roads from Lukachukai and Crystal join (one-half mile north of Green Knobs).

Wingate formation

Because it is thin, this rock probably is without commercial interest.

Entrada sandstone

This uniform, massive, well-exposed, and accessible sandstone offers, in our opinion, very good possibilities for commercial operations on a large scale. The Window Rock area would be a logical starting point because of low-cost transportation from this place to points south and north.

Summerville formation

Although the Summerville formation consists of a thick succession of gray and pink sandstones, the very change in colors may impose problems in the sale of this rock. Probably, also, the properties of the layers of contrasting colors vary, so that the stone might not conform to a definite set of specifications. The layers break into slabs too thick for flagstone, yet too thin for dimension stone.

Morrison formation

The sandstones of the higher members of the Morrison formation do not seem to offer good possibilities for marketing. The cement, for one thing, is definitely poorer than in other sandstone formations, and the erratic distribution of coarse, gritty zones is liable to spoil the appearance of larger blocks. Nearly all the larger outcrops of these sandstones are too far from roads to encourage any quarrying operations.

Dakota (?) sandstone and other Cretaceous sandstones

In the area mapped, this rock is too erratic in composition to be of commercial importance. Other Cretaceous sandstones split irregularly and are poorly situated with respect to transportation.

GRAVEL AND CRUSHED ROCK

At present, the most suitable material for road foundations and aggregate for macadam and concrete highways is minette obtained from pits at Black Rock, Outlet Neck, and Fluted Rock. For the most part, the loose talus debris has been used. Of necessity, it includes a certain proportion of undesirable, highly porous and decomposed material, but it can be obtained close by the road, and without blasting. The ledges that can be drilled and blasted will provide a better quality of road metal, but at higher cost. Should blasting be resorted to, it would be desirable to select the particular face with care. Some portions are massive, solid rock, whereas others are porous minette-breccia, resembling cinder in many respects; the latter would be easier to drill and perhaps is of equal quality.

The western part of the area lacks gravel deposits completely, and the only other rock that could compete with the minette for road-metal purposes is the Shinarump conglomerate. In some sections, this rock consists of loose chert pebbles, an almost ideal composition of road metal. Unfortunately, however, this type of loose chert gravel is distributed in erratic fashion through the region. The best tract worth investigating is the north-south trending upland, north of Fort Defiance, extending from a point 2.9 miles north of the village to a point 6 miles north. The best possibilities of finding suitable gravel patches are east of the gravel road.

Should it be decided to improve the road from Fort Defiance to Red Lake, or the road that leads from Sawmill northeastward, north of Buell Park, towards Sonsela Buttes, Shinarump gravel could be used on a limited scale. The outcrops of the Shinarump conglomerate, north and northeast of Buell Park, have been disintegrated locally, so that here, too, chert pebbles form pockets on the ground. However, none of these deposits is believed to be thicker (deeper) than 10 to 15 feet. Some are much thinner.

Terrace gravels east of U.S. Highway 666 are being crushed by the State Highway Department for use as road metal. Although relatively thin (seldom exceeding 20 ft), these deposits are widespread near the highway (fig 2), and furnish a fairly resistant material for road-building use.

Material for road improvement in the Tohatchi quadrangle south and west of Mexican Springs could best be obtained from beds of shale which have been baked and indurated by the burning of coals. These are best exposed on the north fork of Catron Creek, and are accessible at one point near the creek level. They are indicated by a special symbol on Plate 1 and Figure 2.

SEMIPRECIOUS STONES

From detritus accumulated by ants on the bottom of Buell Park, many pounds of olivine and pyrope crystals can be collected in a few minutes. These stones average 2-3 mm in diameter, but generally they are clear and of a pleasing color. Though the labor necessary to cut and polish them into ring stones or "seeds" would seem to preclude any larger, commercially profitable operation, these crude semiprecious stones probably would sell at a modest profit if marketed in novelties especially designed to bring out their color. They could be inserted, for example, in small "lucite" boxes, or in cheap trinkets, paperweights, ashtrays, book ends, inexpensive pins or bracelets, and could constitute a special Navajo jewelry. A little good, sincere promotional information about the nature and provenance of the stones, plus a little ingenuity in devising inexpensive specialties to make use of them, could create a market demand. Certainly, if the public is educated about the origin and intrinsic quality of these stones, it should be disposed to pay a reasonable price for them.

When the kimberlitic nature of the tuff at Buell Park (fig 2) was recognized, that area was searched with care because there is a remote possibility of locating diamonds in this rock, which, in South Africa, is the primary parent rock of diamonds. Samples collected from the most promising patches of gravel and sand washed from the tuff, as well as from specimens of bedrock, have yielded no diamonds to date.

This, of course, is no proof that the tuff is completely free of diamonds, but it suggests that extensive sampling of the whole diatreme, probably supplemented by trenching, would be necessary to decide whether any diamonds are present. It should be emphasized that diamond is an exceedingly rare mineral in any kimberlite area. Of more than 250 South African pipes, only 25 have encouraged commercial exploitation, and the great bulk of all South African stones have been recovered in 7 pipes (E. Kaiser, 1931, p 20). Even in commercial mines, the concentration of diamonds is less than 1/22,000 of 1 percent (Du Toit, 1926, p 404), and it is obvious that only the processing of large volumes of rock can definitely decide whether diamonds are present, and approximately in what amounts. To undertake so large a project was beyond the scope of the present survey.

The detritus of the small, bare hill near the center of Buell Park contains the largest concentration of olivines and pyrope garnets discovered to date. In the authors' opinion, any large-scale testing operations should commence at this central area, and should include the low outcrops, about 1,000 to 1,500 feet east-southeast of the kimberlite tuff hill. The lapilli tuff also may be considered a potential parent rock, but since it contains fewer olivines and pyropes, it could be that diamonds, too, are rarer in this tuff than in the central phase. This argument is not necessarily valid, but it appears reasonable enough to be considered.

MINERAL FUELS

COAL

In spite of the encroachment during recent years of liquid fuels upon the position of coal as the primary source of power in our economy, it still remains the main reserve, with potential energy stored in the ground greater than from all other sources combined. In New Mexico it is still the largest source of assured energy, with the possible exception of uranium; McKinley and San Juan Counties contain more than 75 percent of the State's total reserves, according to recent estimates (Read, et al., 1950, p 130).

As the demands for energy increase with New Mexico's expanding industrialization, and as the more rapidly expendable resources of oil and gas are depleted, coal eventually may regain a more important position. New technological developments now well under way may possibly play a part in this renaissance. In certain circumstances coal can be burned underground and the resulting gases and heat utilized. It can be liquefied through the process of hydrogenation, producing up to 50 percent by weight of artificial oil, which can be used as fuel. For several decades, the oil-poor countries of Germany and Japan (and more recently England) have been producing hundreds of thousands of tons of gasoline per year in large coal-hydrogenation plants (Storch, et al., 1941, p 1). The liquids produced by this process, although now being used largely as fuels, are also amenable to production of a multitude of bulk organic chemicals such as phenol, cresols, xylenols, benzene, toluene, xylene, solvent naphtha, and many others; in this direction, coal may prove to be of great value in the establishment of chemical industries. Coals from San Juan Basin have already been tested for use in hydrogenation and gasification, and have been shown to be suitable for these purposes. However, the need for a large quantity of water for a plant of any size probably will prevent development of such an industry in this area.

Coal crops out in Tohatchi quadrangle in a belt which extends from the northern edge of the map just east of Todilto Park to the southern edge of the map on the headwaters of the south forks of Catron Wash (fig 2). This belt is occupied by rocks of the Cretaceous system, and coal seams appear in several formations, although beds more than 30 inches thick (at present considered to be of "commercial thickness") are restricted to formations of the Mesaverde group. In the Dakota (?) sandstone coal occurs as thin seams within the shale and siltstone below the main sandstone beds; it also occurs between the thin upper sandstones. Its distribution is erratic and discontinuous, and at no place was it seen to be thicker than 24 inches. It, therefore, is not considered to be of economic value at the present time.

Within the Mesaverde group, carbonaceous siltstone and shale, lignitic clays, and coal appear at several horizons, and are found among the shaly intervals between the sandstone tongues of the Gallup sandstone, throughout the Crevasse Canyon formation, through the lower 500 feet of the Menefee formation, and in the lower member of the Tohatchi formation. However, coal beds with thicknesses of more than 30 inches were found only in the lower Gibson member of the Crevasse Canyon formation and in the lower 150 feet of the Menefee formation (lower part of the upper Gibson coal member of Sears, 1934).

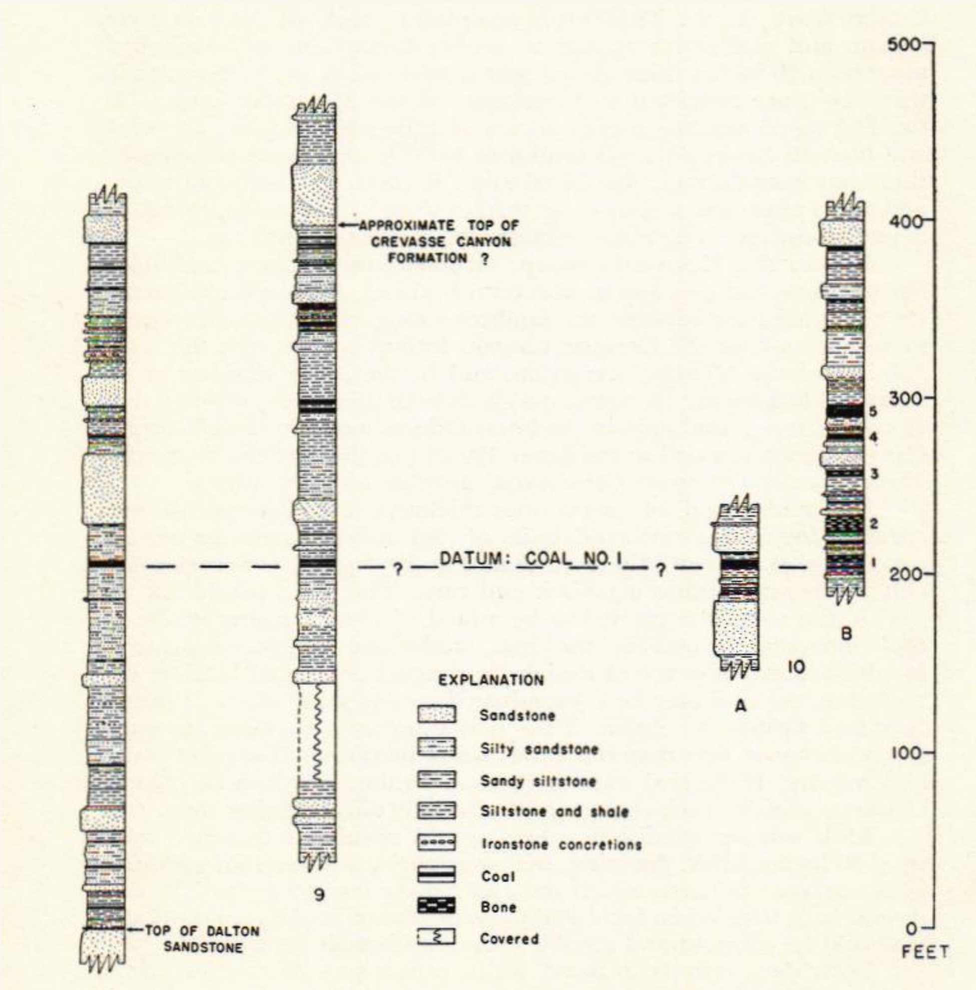
It is understood, of course, that thickness of bed is not the only criterion for commercial availability of coal under present-day mining conditions. If the beds dip more than 8 or 10 degrees, it becomes difficult to operate mining machines and cars. The more nearly flat the coal is, the more cheaply it can be mined. Unless a strong sandstone roof immediately overlies the coal, additional mining expense is involved in excessive use of timber for support or in roof bolting; furthermore, the coal may be contaminated to the point where it cannot be mined profitably. Again, if the coal seam itself contains too many layers of clay or bony material, such contaminations will prevent profitable mining. If the coal seam thickens and thins, or otherwise changes character rapidly, such changes will adversely affect mining costs.

Ideal mining conditions, then, would require a coal bed more than 30 inches thick, flat-lying, with a strong sandstone roof requiring little support and from which the coal breaks away cleanly. The coal should have little or no included seams of contaminating material, and it should be constant and regular over considerable distances.

With these criteria in mind, let us return to a description of the coals in Tohatchi quadrangle.

The beds in the northern part of the coal belt dip eastward from 20 to 35 degrees, and in no place were they seen to be covered by sandstone. Along the southern half of the belt they dip from 5 to 19 degrees, with an average dip of perhaps 15 degrees. Several beds were observed to have good sandstone roofs. Throughout the area, the thickness of the individual beds varies greatly within short distances, and the thickness of included seams of clay or shale also varies rapidly from place to place. Many of the beds which otherwise would be of value include seams of this sort whose thickness exceeds that of the contained coal.

The following measured sections of coals give an idea of the characteristics encountered throughout the area; a composite sketch of four rock sections containing coal is given as Figure 3.



MEASURED SECTIONS OF COAL-BEARING ROCKS IN THE SOUTHWEST PART OF TOHATCHI QUADRANGLE (SEE PL 11 AND FIG 2 FOR LOCATION).

Figure 3

Localities where coals of commercial thickness crop out are shown on Figure 2 A-E. Measured sections of these coals are tabulated in order of their location from north to south.

A. North Fork Todilto Wash, Dilco member. Dip 22° E.

	Ft	*in.*
Gray and carbonaceous shale	25	
Coal		6
Thin-bedded sandstone and shale	10	
Coal		8
Pale-gray clay		6
Coal	*3	

Gallup sandstone.

B. One mile south of Squirrel Springs Wash, upper Gibson part of lower Menefee formation. Dip 8° E.

	Ft	*in.*
Pale yellow-orange friable sandstone	6	
Carbonaceous shale	6	
Coal	2	
Pale-gray clay siltstone		3
Clayey lignite	1	
Gray silty carbonaceous shale	2	
Coal	*6	
Fissile carbonaceous shale	2	
Fissile gray shale	2	
Pale-buff sandstone and olive-yellow shale	20	

About 20 feet above top of Point Lookout sandstone. Interval covered.

C. East of mouth of Crevasse Canyon, upper Gibson part of lower Menefee formation. Dip 12° E.

	Ft	*in.*
Pale-yellow medium-grained channel sandstone	5	
Bright coal	*3	
Olive-yellow siltstone	1	
Carbonaceous shale	6	
Yellow silty clay with jasper septarian nodules near top and at base	10	

About 100 feet above top of Point Lookout sandstone.

D. Creek bed 1 mile southwest of mouth of Crevasse Canyon, base of Menefee formation. Dip 8° SE.

	Ft	*in.*
Massive crosslaminated sandstone	10	
Gray carbonaceous shale	1	
Crosslaminated sandstone		10
Bright coal	*2	8
Gray clay		6

Top of Point Lookout sandstone.

* Minable coal.

E. Three coal beds were both measured and sampled on the south fork of Catron Creek. Coal No. 5 crops out in the south wall of the main creek at the forks where the wagon trail starts up the ridge toward Fort Defiance.

Coal No. 5. At creek forks, 75 feet south of road. Attitude of bed N. 20° W., 19° E. (pl 3-B).

	Ft	*in.*
Platy, thin-bedded, yellow-gray sandstone	6	
Massive yellow-gray sandstone	2	5
Coal		*3
Pale yellowish-brown clay		3/8
Coal		*8
Pale yellowish-brown shale		1 5/8
Coal	*3	5 3/4
Olive-gray shale	1	1
Coal		*11 1/2
Olive-gray shale	6	
Coal		11
Coal sampled (E-19770)	*5	4 1/4

Coal No. 3. 900 feet N. 75° W. of creek forks. Attitude of bed N. 24° W., 16° E.

	Ft	*in.*
Dark yellowish-brown carbonaceous shale	7 plus	
Coal	*3	11 3/4
Light gray carbonaceous shale	6 plus	
Coal sampled (E-19771)	*3	11 3/4

Coal No. 1. 1700 feet N. 67° W. of creek forks. Attitude of bed N. 30° W., 8° NE. (pl 3-C).

	Ft	*in.*
Thin-bedded, fine-grained, yellow-gray sandstone	2	6
Gray papery shale		6
Massive and papery bone and boney coal	8	
Bright coal	1	6
Silty carbonaceous shale	1	7
Pale-gray, medium-grained, friable sandstone	2	1
Coal	1	5
Black carbonaceous papery silty shale	1	11
Fine-grained gray to orange sandstone	1	
Dark-gray carbonaceous shale	3	6
Coal	*2	1
Light olive-gray sandy shale		1 3/4
Coal	*1	1 1/4
Pale gray-olive papery shale	1	
Coal	*1	4 1/2
Pale gray-olive papery shale	2	
Coal sampled (E-19772)	*4	6 3/4

* Minable coal.

It may be seen that, even by present-day mining criteria, several of the above coals have possibilities of commercial operation under sufficient demand. Of these, the No. 5 coal on Catron Creek appears to exhibit the best combined characteristics. This coal was traced on the surface for more than 2 miles, and continues southward beyond the edge of the map. Its course is plotted on Figure 2 and Plate 1. Insufficient time was available to trace the outcrop trend of the other coals, although the course of a coal at the base of the Menefee formation closely parallels the contact with the Point Lookout sandstone over much of its length.

Many of the carbonaceous zones and coal beds have been burned in the past, and these areas are plotted by a zigzag symbol (fig 2 and pl 1). As a result of this burning, the exposures of the baked and indurated shale and slag stand out prominently as red cliffs; these cliffs are particularly prominent a mile south of Crevasse Canyon and on the headwaters of the south fork of Catron Creek.

TABLE 1. SAMPLE DATA AND ASH FUSION TEMPERATURES OF COALS FROM SOUTH FORK OF CATRON CREEK*

Number of coal bed (fig 2)	1	3	5
Bureau of Mines Laboratory number	E-19772	E-19771	E-19770
Interval sampled	5' 81/2"	3' 113/4"	6' 71/2"
Amount of sample rejected	1' 13/4"	none	l' 3"
True thickness of coal beds sampled	4' 63/4"	3' 111/2"	5' 41,4"
Initial deforming temperature °F	2680	2700	2360
Softening temperature °F	2810	2840	2600
Fluid temperature °F	2910 plus	2910	2730

*U.S. Bureau of Mines, Fuels Utilization Branch.

Analyses of the three coal beds sampled are given in Tables 1 and 2, and are compared with analyses of coals from nearby mines in San Juan Basin and with one of the large mines in Colfax County. It may be seen that, as compared with the other coals, the local analyses are high in moisture and in oxygen, and low in carbon and heat value. This is an expected result of the sampling, which was of necessity taken from near-surface exposures rather than from beds hundreds of feet underground. Surface oxidation of the coals is evident, but the equivalency of the percentages of volatile matter, ash, hydrogen, nitrogen, and sulfur indicate that truly fresh samples of the local coal would be of equal rank and value with those of the other coals from San Juan Basin. The Raton coal sample is even higher in carbon and heat value; it is of coking grade and consequently of value to the steel industry.

Subbituminous coal weighs about 80 pounds to the cubic foot, or 25 cubic feet to the ton (Moore, 1940, p 267). A bed 1 foot thick weighs approximately 1,700 tons to the acre. If the bed were 3 feet thick, the weight would be 5,100 tons per acre, and so on. Underground mining gives only a 70 to 80 percent recovery of coal, since in most places pil-

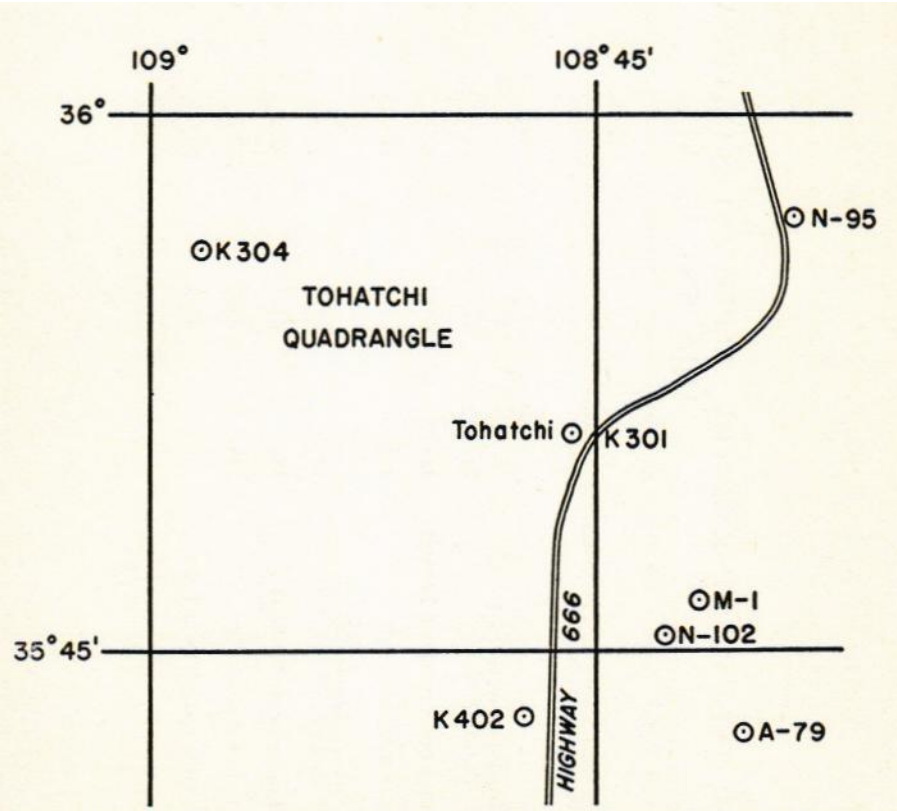
TABLE 2. COAL ANALYSES, COMPARED WITH OTHER NEW MEXICO COALS

Sample Location	Condition of Coal[1]	Proximate Analysis				Ultimate Analysis					Heat Value in British Thermal Units per Pound
		Moisture	Volatile Matter	Fixed Carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur	
No. 1. Catron Creek (fig 2 and pl 3-B).	A	13.7	34.3	39.4	12.6	5.1	53.1	1.0	27.6	.6	8,930
	B		39.8	45.5	14.7	4.1	61.6	1.1	17.8	.7	10,360
	C		46.6	53.4		4.8	72.2	1.3	20.9	.8	12,130
No. 3. Catron Creek (fig 2).	A	23.1	34.2	37.7	5.0	5.7	50.1	1.0	37.7	.5	8,160
	B		44.4	49.1	6.5	4.0	65.1	1.3	22.5	.6	10,610
	C		47.5	52.5		4.3	69.6	1.4	24.0	.7	11,340
No. 5 Catron Creek (fig 2 and pl 3-C).	A	23.6	33.0	33.9	9.5	5.4	45.4	1.0	38.2	.5	7,340
	B		43.1	44.4	12.5	3.6	59.4	1.3	22.6	.6	9,610
	C		49.3	50.7		4.2	67.8	1.5	25.8	.7	10,980
Navajo Tribal coal mine[2] 10 mi SE of Ft. Defiance	A	12.8	35.7	46.7	4.8	6.3	65.5	1.1	21.7	.6	11,630
	B		41.0	53.5	5.5	5.5	75.2	1.3	11.8	.7	13,340
	C		43.4	56.6		5.9	79.6	1.4	12.4	.7	14,110
Tohatchi Indian School[2] 16 mi SE of Tohatchi	A	11.3	35.6	42.6	10.5	6.2	60.9	1.1	20.6	.7	10,830
	B		40.2	48.0	11.8	5.6	68.7	1.2	12.0	.7	12,220
	C		45.6	54.4		6.3	77.9	1.3	13.7	.8	13,850
Gamerco, Navajo No. 5 (composite)[2]	A	11.9	37.2	43.0	7.9	5.9	63.6	1.1	21.0	.5	11,290
	B		42.3	48.8	8.9	5.2	72.2	1.3	11.8	.6	12,820
	C		46.4	53.6		5.7	79.3	1.4	12.9	.7	14,080
Raton, Koehler No. 1 (composite)[2]	A	3.6	36.1	48.3	12.0	5.3	69.8	1.3	10.9	.7	12,620
	B		37.5	50.0	12.5	5.0	72.4	1.4	8.0	.7	13,100
	C		42.8	51.2		5.8	82.7	1.6	9.1	.8	14,960

1. Condition of coal: A, As received; B, Moisture free; C, Moisture and ash free.
2. Ellis, R. W. (1936).

lars must be left to support the roof. Furthermore, the thin top or bottom benches of coal frequently are left in place to serve as a roof or floor. Coal in this region may be mined to depths of 1,500 to 2,000 feet, under favorable geologic conditions. In Tohatchi quadrangle the coal-bearing beds in the southern part of the area do not go below 4,000 feet elevation in the Nakaibito syncline (see pl 1, sec B-B'); hence, if the coal beds were continuous, they could be mined as far east as the Tohatchi Indian School mine in sec. 22, T. 17 N., R. 17 W., or approximately 20 miles to the east.

Coal beds in this area, however, are seldom continuous for long distances, and it is probable that a safe estimation of reserves could be made by assuming an extent underground equivalent only to the extent of the outcrop. The outcrop of the No. 5 bed in the area mapped is 2½ miles long, consequently the conservative estimate of acreage of coal in the area would be about 6 square miles or 3,840 acres. If an average of 4 feet of the 5½-foot bed could be mined from this area,



INDEX MAP SHOWING LOCATION OF DEEP WELLS IN TOHATCHI AND ADJACENT QUADRANGLES (NUMBERS REFER TO TABLE 3).

Figure 4

TABLE 3. DATA ON SOME OF THE DEEPER WELLS IN TOHATCHI QUADRANGLE AND ADJACENT AREAS

BUREAU OF INDIAN AFFAIRS No.	NAME OR APPROXIMATE LOCATION	DEPTH (feet)	ELEVATION (feet)	To OF DALTON SANDSTONE (El. feet)	Completed In	WAFER FROM
K-304	Humble Navajo No. 1 Todilto !'ark	2479	7270+	....	Quartzite	
N-95	10 1/2 miles north of Tohatchi	1185	5926	4925	Crevasse Canyon	Dalton sandstone
K-301	Tohatchi deep well	1790	6470	4800	Crevasse Canyon	Point Lookout sandstone
M-1	Artesian well 8 miles southeast of Tohatchi	1150	6113	5212	Gallup sandstone	Dalton and Gallup sandstone
N-102	2 miles southwest of M-I	1353	6144	5272	Gallup sandstone	Gallup sandstone
K-402	Twin Lakes School	1497	6550	5200	Gallup sandstone	Gallup sandstone
A-79	5 miles east of Twin Lakes	873	6243	5630	Gallup sandstone	Gallup sandstone

the total tonnage would amount to more than 25 million tons, 75 percent of which would be nearly 19 million tons of available coal—from this one bed. McKinley County since 1882 has not produced much more than 24 million tons. The Window Rock coal mine, located 8 miles southwest of Catron Creek, produces an average of about 15,000 tons per year.

OIL AND GAS

By reason of the thin nature of the Permian and Triassic section which borders and overlies the Defiance uplift in Fort Defiance quadrangle, the possible presence of oil or gas within the mapped area is restricted to Tohatchi quadrangle.

The periphery of San Juan Basin has been explored by numerous test wells within the last few years with the notable exception of the southwest quadrant, from Stony Butte, 30 miles east, to near Sanastee and Table Mesa, 40 miles north of the area mapped. Only six wells deeper than 1,000 feet have been drilled within or adjacent to the area, and none of these has shown oil.

According to Barnes and Arnold (1951, p 140), among the 23 oil and gas fields in San Juan Basin which produce from the following geologic formations, type of production may be divided as follows:

TABLE 4. DISTRIBUTION OF PRODUCING SAN JUAN BASIN OIL AND GAS FIELDS BY FORMATIONS

FORMATION	OIL	OIL & GAS	GAS
~~Kirtland shale and Farmington sandstone~~	~~—~~	~~1~~	~~3~~
Fruitland formation	—	—	-
Pictured Cliffs sandstone	—	—	3
Lewis shale	—	—	-
Mesaverde group	4	—	2
Mancos shale	3	—	-
Dakota (?) sandstone	6	1	3
Jurassic system	—	—	-
Permian system	—	—	-
Pennsylvanian system	1	1	2

The Dakota (?) sandstone, Mancos shale, and Mesaverde group underlie nearly all of Tohatchi quadrangle. Along the eastern edge of the area the base of the Dakota (?) lies at elevations ranging from 2,800 to 4,200 feet, or at depths from the surface (6,200 ± 100) of from 2,000 to 3,400 feet. Along the axis of the Nakaibito syncline the thickness may exceed this latter figure. Figure 17 shows the elevation of the top of the Dakota (?) sandstone by means of contours.

Since Pennsylvanian rocks are absent or of negligible thickness in the area studied, the geologic units of potential importance probably include only the Dakota (?) sandstone and the sandstone members of the Mesaverde group. There is an underlying 1,300-foot section of Jurassic rocks, mostly sandstones, but these rocks have not yet been producers in San Juan Basin.

Some 93 "structures" in San Juan Basin which either are producers, have been drilled, or are as yet untested, have been classified by Barnes and Arnold (1951, pp 132-140) according to the type of trap.

TABLE 5. DISTRIBUTION OF SAN JUAN BASIN POTENTIAL TRAPS BY "STRUCTURAL" TYPES

TYPE OF TRAP	PRODUCERS	DRILLED	UNTESTED
Anticlines	11	41	29
Faults	1	0	1
Stratigraphic traps	4	6	0
Synclines	0	0	1

Of the three types of traps which previously have produced in San Juan Basin, it is highly probable that oil or gas will be found in a stratigraphic trap, if anywhere within the mapped area. No faults of any importance have been found within the area, and the Nakaibito syncline is the only large-scale fold in the eastern part. The Todilto Park dome has been drilled unsuccessfully (Humble Navajo No. 1, above), and the nature of the section penetrated is unfavorable.

The lenticular nature of the Dakota (?) and lower Mesaverde sandstone units (fig 13) suggests that they may furnish the most favorable environment for oil accumulation in the area. Rapid lateral facies changes from sandstone to siltstone or shale are common in the outcrop sections; similar changes underground might furnish locations for possible updip accumulation of fluid hydrocarbons.

GROUND WATER

by F. X. Bushman

EXISTING GROUND-WATER SUPPLIES

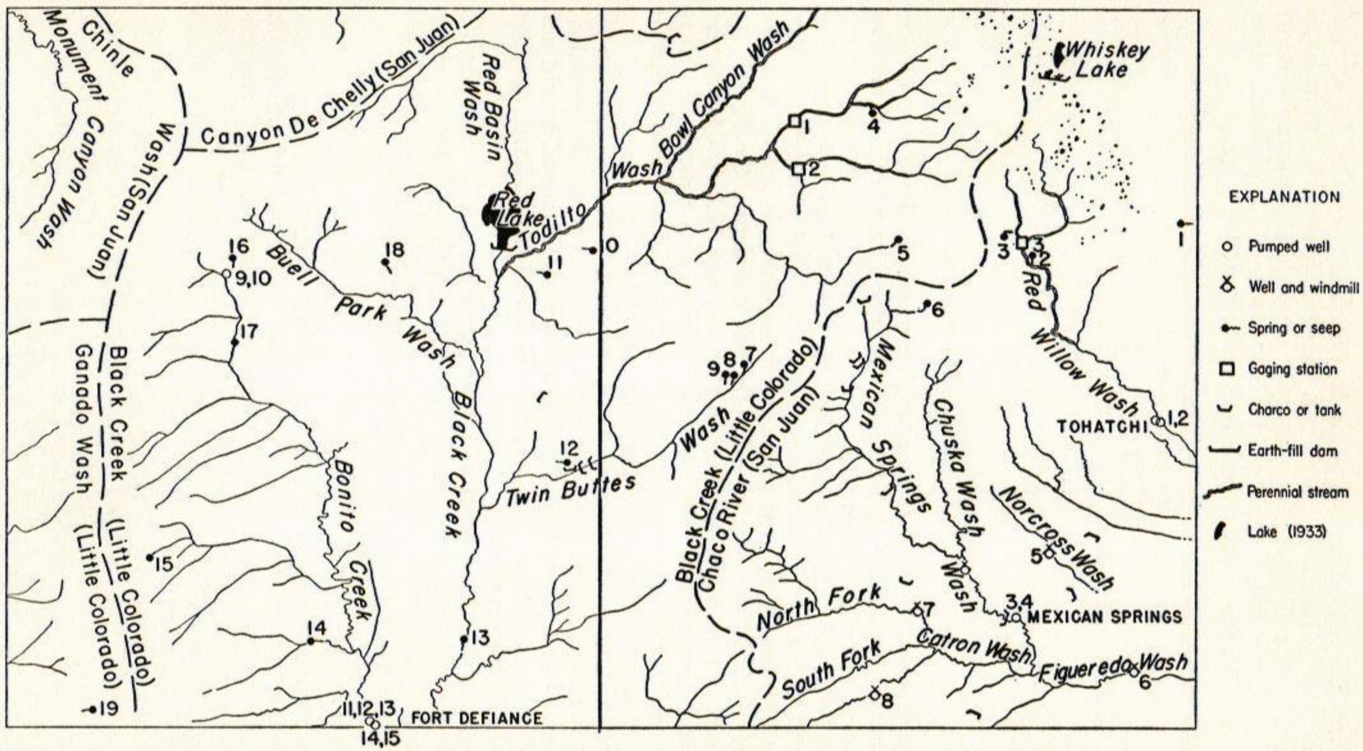
Records of wells and springs in Fort Defiance and Tohatchi quadrangles are shown in Tables 7 and 8. The left-hand column in both tabulations is the reference to the location indicated on Figure 5, which shows the surface-water resources and wells in Fort Defiance and Tohatchi quadrangles, 1953.

Tohatchi

The water supply at Tohatchi is obtained from two drilled wells. The Tohatchi deep well (No 2, fig 5) was drilled to a depth of 1,790 feet. According to the driller's log, the main source of water in this well was obtained from a sandstone between 1,275 and 1,354 feet, which is probably the Point Lookout sandstone. The yield was reported to have been 63 gpm. Additional water was obtained in "sands" both above and below the principal aquifer.

At the present time the well is equipped with a Peerless Hi-Lift deep-well pump. The pump setting was reported to be 465 feet with an airline set at 460 feet. Capacity of the pump was reported to be 25 gpm.

Figure 5



INDEX MAP SHOWING DRAINAGE BASINS, SURFACE-WATER RESOURCES, AND WELLS IN FORT DEFIANCE AND TOHATCHI QUADRANGLES (NUMBERS REFER TO TABLES 7 AND 8).

On March 25, 1953, after the pump had been in operation for several hours, the water level in the well was 239 feet below the pump base. Ten minutes after the pump stopped, the water level had recovered to 212.5 feet. The recovery figures are shown below. Water levels were determined with the airline and direct-reading airline gage.

MINUTES AFTER STOPPING	WATER LEVEL (in feet)	MINUTES AFTER STOPPING	WATER LEVEL (in feet)
0	239	6	215
1	229	7	214
2	224	8	213.5
3	220	9	213
4	218	10	213.5
5	216		

These values, when plotted on semilog paper, indicate a coefficient of transmissibility of 366 gallons per day per foot width of aquifer under a gradient of 100 percent.

The Tohatchi shallow well (No 1) is reported to have been dug to a depth of 80 feet originally, with a horizontal collection gallery placed at that level. Later the lower portion of the well was filled to the 57-foot level, which is reported to be the present depth. On March 25, 1953, the nonpumping water level in the well was 18.5 feet below the pump base. The measurement was made with a steel tape. The well is maintained for standby purposes and reportedly had not been in operation for several months previous to the time of study.

A water sample was collected from the deep well (No 2, table 9). No sample was collected from the shallow well because the prelubricating water line was partially open and the water obtained would not have been representative. The water is mineralized and hard, and has an odor of hydrogen sulfide.

The driller's log of the deep well is tabulated here. The stratigraphic breaks were determined by J. E. Allen by correlation with logs of other wells located both in and beyond the two quadrangles, together with the study of surface geology (see fig 4; and K-301, table 3).

Mexican Springs

Two wells are located at Mexican Springs. One (No 4, fig 5) was a 39½-foot deep caisson constructed in 1934. A 300-foot-long infiltration gallery reportedly emptied into the caisson. It is reported to have produced 55 gpm upon completion. Records of the U. S. Geological Survey Ground Water Branch at Holbrook, Arizona, indicate the yield may have dropped as low at 2½ gpm in 1948.

The second well (No 3) was completed at a depth of 64 feet. The yield of this well was reported to have been 18 gpm with a drawdown of 20 feet below a nonpumping level of 35 feet. By reason either of decreased yield or increased demand, or a combination of both factors, the well was redrilled in 1953. No reports on final depth, yield, or water levels were obtained.

TABLE 6. DRILLER'S LOG OF TOHATCHI DEEP WATER WELL

FORMATION	THICKNESS (in feet)	DEPTH (in feet)
Menefee formation		
sand and gravel	34	34
blue shale	76	110
gray shale	15	125
brown shale	109	234
brown sandy shale	81	315
sand water	4	319
brown shale	26	345
brown sandy shale	50	395
sand, water, 5 bailers per hour	5	400
blue shale	138	538
sand, water	12	550
blue shale	20	570
sand, water, raised to within 300 feet of surface	25	595
hard sandy shale	5	600
brown shale	25	625
hard sandy shale	5	630
sand, water	30	660
white sand	25	685
gray sandy shale	10	695
brown shale	25	720
gray sandy shale	10	730
sand, water	25	755
brown shale	3	758
hard sandy shale	7	765
gray sandy shale	44	809
sand, water	12	821
blue shale	3	824
brown shale	13	837
gray shale	7	844
hard brown shale	4	848
hard sand	6	854
sand, water	16	870
brown shale	10	880
gray shale	20	900
gray sandy shale	12	912
brown shale	18	930
gray shale	40	970
hard shale	1	971
gray shale	69	1040
soft gray shale	15	1055
gray sand shale	9	1064
blue shale	6	1070
hard shale	2	1072
blue shale	13	1085
brown shale	35	1120
gray shale	5	1125
blue shale	10	1135
brown shale	5	1140
light gray shale	15	1155
gray shale	35	1190
sand, water	6	1196
gray sandy shale	44	1240
brown shale	23	1263
sand, water	1	1264
coal	6	1270
brown shale	5	1275
Point Lookout sandstone		
sand, water, raised within 240 feet of surface, tested 63 gpm	79	1354
gray sandy shale	62	1416
sand, water	39	1455
Lower Gibson member		
brown shale	11	1466
sand, water	6	1472
gray sandy shale	20	1492
sand, water	38	1530
hard shale	4	1534
sand, water	6	1540
hard shale	2	1542
gray sandy shale	8	1550
sand	6	1556
gray sandy shale	54	1610
sand, water	14	1624
gray shale	41	1665
Dalton sandstone (?)		
sand, water	20	1685
Dilco member		
brown shale	10	1695
coal	5	1700
sand, water	8	1708
gray shale	7	1715
coal	3	1718
brown shale	72	1790
	Total depth	1790

The driller's log of the original 64-foot well indicated that the source of the water was the sandstone below the alluvium.

FORMATION	THICKNESS (in feet)	DEPTH
alluvial fill	48	48
sandstone, hit water at 54 feet	9	57
clay	7	64
bottom of hole		64

At Mexican Springs, and in the southern parts of both quadrangles, the quality of the water is somewhat poorer generally than at Tohatchi. It has both very high sulfates concentration (487 ppm) and very high hardness (540 ppm).

Norcross Wash well

In 1939, a well (No 5, fig 5) was drilled by the U. S. Irrigation Service in Norcross Wash as part of the experimental program of the Mexican Springs Demonstration Area. The well was completed at a depth of 207 feet and reportedly yielded 10 gpm. Nonpumping level was 20 feet.

The driller's log of units encountered is as follows:

FORMATION	THICKNESS (in feet)	DEPTH	FORMATION	THICKNESS	DEPTH (in feet)
old dug well		22	gray sand, water	15	175
gray sand	10	32	gray shale	5	180
Menefee formation					
blue shale	48	80	gray sand	3	183
gray shale	80	160	gray shale	24	207

The analysis of water from this well (No 5, table 9) indicates a high mineralization (specific conductance 1,600 micromhos, sulfates 681 ppm, hardness 375 ppm). While the water is palatable to livestock, the high sulfates will be unpleasant to humans. The percent sodium is 58. This is near the upper limit for irrigation, depending on the quality of the soil and the quantity of water to be used.

Figueredo Wash Well

Figueredo Wash well (No 6) also was drilled by the U. S. Irrigation Service in 1939. Original depth was 470 feet. Nonpumping level was reported to be 45 feet below the surface, and yield was recorded to be 17 gpm on bailer test.

The well was cased the full depth. The casing reportedly was perforated between 50 and 94 feet and between 160 and 189 feet. The well was gravel-packed from bottom to the surface.

The water obtained from this well is very highly mineralized (specific conductance 2,410 micromhos, sulfates 846 ppm, hardness 58 ppm, and percent sodium 95). Its use should probably be limited to livestock. Humans can drink it without harmful effects, but not without distaste. The percent sodium is too high to permit its use for irrigation. The driller's log was reported as follows:

FORMATION	THICKNESS (in feet)	DEPTH (in feet)	FORMATION	THICKNESS (in feet)	DEPTH (in feet)
Menefee formation					
light gray shale	55	55	dark gray sand, water at 184 feet	14	184
gray sand dark	7	62	dark gray shale dark	76	260
gray shale dark	3	65	gray sand, water	14	274
gray sand dark	26	91	dark gray shale gray	58	332
gray sand and gravel	4	95	sand, water gray	13	345
dark gray shale	75	170	shale, bottom	125	470

Sawmill

A well (No 9, fig 5) was drilled at Sawmill in 1942 to a depth of 845 feet. No water was found below a depth of 38 feet and the lower portion of the hole reportedly was plugged. It was stated that, at one time, the hole was used as a shallow well, but in 1953 the site was under the corner of a building.

The driller's log was reported as follows:

FORMATION	THICKNESS (in feet)	DEPTH (in feet)	FORMATION	THICKNESS (in feet)	DEPTH (in feet)
Cutler formation, bottomed in Precambrian quartzite					
alluvial fill	15	15	light gray sandstone	5	769
sandstone, light red	7	22	sandstone, reddish brown, quartz	15	784
sandy shale, light red	17	39			
sandstone, light red	4	43	gray sandstone, very hard	2	786
shale, red	19	62			
sandstone, reddish brown, very hard	628	690	gray sandstone, very• hard lenses	12	798
sandstone, reddish brown, very hard	74	764	fine quartz	47	845

The community now obtains its water from a gravel-filled sump, 3 miles southeast of town, excavated in the alluvium of Bonito Wash, with a 38-foot well available on a standby basis. This sump, shown in Table 8 as a spring, reportedly has a safe yield of 70,000 gallons per day. No sample was obtained, but the water probably is mineralized and hard.

Fort Defiance

The principal source of water for the Fort Defiance community is reported to be an infiltration gallery located above the village in Bonito Canyon. Mr. Shuman, water station engineer, reported that the infiltration gallery as originally constructed consisted of three adjacent,

TABLE 7. RECORD OF WELLS

Map No.	Well Name and Location	Year Drilled	Depth of Well (feet)	Diameter of Well (inches)	Water Level Below Surface Feet	Water Level Below Surface Date
W1	Tohatchi shallow well		57		18.6	3/25/53
W2	Tohatchi deep well		1790		[1]212.5	3/25/53
W3	Mexican Springs drilled		64 (?)	6⅝ (?)	35	
W4	Mexican Springs dug	1934	39½ (?)	31 feet (?)	[2]30.8	9/23/48
W5	Norcross Wash	1939	207	8⅝	20	R
W6	Figueredo Wash well ⅛ mi W of Hwy 666	1939	470	6⅝	45	R
W7	North fork, Catron Wash					
W8	South fork dug well					
W9	Sawmill dry hole	1942	845	12½		
W10	Sawmill shallow well		38			
W11	Ft. Defiance infiltration gallery		22	10′ pit, 8″ casing	8-14	R
W12	Ft. Defiance infiltration gallery		22	10′ pit, 8″ casing		
W13	Ft. Defiance infiltration gallery		20	10′ pit, 8″ casing		
W14	Ft. Defiance caissons				[2]12.6	9/20/51
W15	Ft. Defiance caissons					

1. Water level not fully recovered, pump off 15 minutes.
2. Water level measured by U.S.G.S. Ground Water Branch.

TABLE 7 (continued). RECORD OF WELLS

MAP No.	*METHOD OF Lift	PUMPING RATE gpm	Reported	**Use	INDIAN SERVICE WELL No.	REMARKS
WI	D			P	K-301	Very seldom used
W2	D	25	R	P	K-301a	Reported tested at 75 gpm with 150-200 ft drawdown. Pt. Lookout sandstone
W3		18				Redrilled 1953, drawdown to 55' at 18 gpm. Source probably is alluvium
W4		55	R			
W5	W			S	14M71	Originally dug well to 22', reported bailed at 10½ gpm. Menefee formation
W6	W			S	N39	Reported bailed at 17 gpm, gravel packed. Menefee formation
W7	W					
W8	W			D,S	14N106	Concrete platform and trough, hand pump
W9		30	R			Not used
W10						Standby service
W11	C, G					
W12	C, G	250	R	I'		Originally boxed-in springs (?), later casings installed below bottom of pits. Cutler formation and alluvium
W13	G					
W14	Test pump	242				Drawdown to 16.2 after 6 hrs. Alluvium
W15						

* Method of lift: 1), deep well turbine; W, windmill with cylinder; C, centrifugal; G, gravity flow •• Use: P, public supply; S, stock; D, domestic

TABLE 8. RECORD OF SPRINGS

MAP No.	SPRING NAME AND LOCATION	IMPROVEMENTS	YIELD	• USE	KIND OF OPENINGS	GEOLOGIC HORIZON TYPE OF ROCK
Si	E of Deza Bluffs	None	<1 gpm	D, S	Seep	Chuska sandstone
S2	Pine Springs, Red Willow Wash	Concrete box	<1 gpm	D (?)	Seep	Base of Chuska sandstone
S3	Ind. Serv. #144.1S, head of side tributary to Red Willow Wash	Concrete box, piped to trough	<I gpm	D, S	Seep	Chuska sandstone
S4	North fork, Todilto Wash	None	I -5 gpm	S	Seep	Chuska sandstone
S5	Squirrel Spring	Excavated rock	1-5 gpm		Well 3' square cut 2' deep in sandstone	Chuska sandstone
S6	Head of Mexican Springs Wash	Block stone and concrete trough	<I gpm	D,S		Chuska sandstone
S7	1 mi E of Twin Buttes	None	<1 gpm	D	Seep	Gallup sandstone
S8	I mi E of Twin Buttes	None		1)	Seep	
S9	1 mi E of Twin Buttes	None		D	Seep	
S10	West draining canyon, N base of Zilditloi Mtn.	None	1 qt/min	none	Crack	Top of Summerville
S11	1000 ft SE of The Beast	Wooden cover		D	Seep	Base of Summerville
S12	mi N of Twin Buttes Wash	None		S	Seep	Base of Summerville
S13	Black Creek	Wooden cover		D	Seep	Alluvium
SI4				D, S	Perennial waterhole in stream bed	Cutler sandstone
S15				none	Waterhole	De Chelly sandstone
S16	NE of Sawmill in wall of canyon	Boxed		D	Box cut in sandstone	Dc Chelly sandstone
S17	Tribal Sawmill spring	Excavated sump	70,000 gpd	D, M		Alluvium
S18	Buell Park	None			Waterhole	Alluvial cover
S19	N part of Ft. Defiance quad.	None	<1 gpm	S	Waterhole in stream bed	De Chelly sandstone

• Use: D, domestic; S, stock; M, sawmill.

concrete-walled pits, each 10 feet square and 10 feet deep. Later, 8-inch wells (Nos 11, 12, 13; fig 5) were drilled in the bottom of each pit, two of these wells being drilled to 22 feet and one to 20 feet. Still later, the water levels dropped below the bottom of the pits and pumps were placed in the line. At the same time the shallower of the three wells was disconnected.

Approximately three years ago, four test holes were put down in a line across the canyon to depths of from 12 to 18 feet. Yields ranged from 100 gpm to 350 gpm.

In 1951, two large-diameter concrete caissons (Nos 14, 15; fig 5) were constructed in the canyon floor downstream from the infiltration gallery. According to a memorandum by S. E. Galloway, U. S. Geological Survey Ground Water Branch at Holbrook, Arizona, one of the caissons was tested on September 20, 1951, at a rate of 242.4 gpm. The drawdown at the end of six hours and 25 minutes of pumping was 3.53 feet lower than the original nonpumping level of 12.65 feet below the edge of the manhole. It was reported that the water level in the adjacent caisson lowered 3.47 feet during the test period. In March, 1953, though one of the caissons was equipped with a turbine pump, it was not being used to furnish water to the system.

A water sample was collected at the pumping station in the village. The results of the analysis are shown in Table 9 (No. 11) . The water is mineralized (specific conductance 541 micromhos) and hard (244 ppm) and is well within limits of use for domestic purposes, livestock watering, and irrigation.

GROUND-WATER AVAILABILITY BY GEOLOGIC UNITS AND AREAS*

The mapped area falls conveniently into three divisions under which the water-bearing geologic units and the availability of this water may be discussed. These consist of: I) the pre-Cretaceous area west of the Dakota (?) sandstone cuesta, including all of Black Creek Valley, Todilto Park, and the Defiance Plateau to the west; 2) the area of Cretaceous rocks in the Manuelito Plateau and Chuska Valley to the east; and 3) Chuska Mountain, underlain by the Chuska sandstone.

Quaternary alluvium, including the Nakaibito formation, slope wash, alluvial fans, talus, and recent alluvium in the gullies, is distributed throughout the area along the main drainage channels. These deposits are of considerable importance for local domestic use, but the amount of water available is small and the quality may be poor. Most of the ground water from these units is derived from small intermittent seeps and shallow-dug wells. Probably most of the water in the Mexican Springs wells (Nos 3 and 4) is derived from the alluvium.

In Area 1, the oldest rocks, Precambrian (?) quartzites, are exposed in so small an area that they have no importance as groundwater carriers. Water in the area south of Sawmill, which is underlain by the Permian Cutler formation, is obtained from natural seeps along the principal courses of intermittent streams, and is being used both for family needs and stock watering. A large collecting sump (spring

* This section was written by Robert Balk and John Eliot Allen.

TABLE 9. RECORD OF ANALYSES OF WATER FROM WELLS AND SPRINGS

Map No.	Analysis[1] No.	Name	Date of Collection	Temp. °F	Silica SiO_2	Calcium Ca	Magnesium Mg	Sodium + Potassium Na+K	Carbonate CO_3
W1		Tohatchi shallow well	1/14/49			56	6.7	21	0
W2	22508	Tohatchi deep well	3/25/53	81	15			38	0
W3	22693	Mexican Springs drilled	5/13/53	54	20			110	0
W4	N.M.A.& M.A.	Mexican Springs dug	1945			206	14	245	0
W5	22692	Norcross Wash well	5/12/53		16			234	0
W6	22694	Figuerdo Wash well	5/12/53	57.5	12			553	22
W11	22509	Fort Defiance[2]	3/27/53	51	13			20	0
G3	22506	Red Willow Wash	3/25/53	38	38			13	0
S2	22505	Pine Spring	3/25/53	47.3	44			10	0
S3	22504	#144.15	3/25/53	35	35			15	0
S5	22507	Squirrel Springs	5/5/53	48	55			16	0

1. Analyses by U.S.G.S., Quality of Water Branch laboratory, Albuquerque, New Mexico.
2. Sample collected at tap in pumping station. No water from new caisson being used.

TABLE 9 (continued). RECORD OF ANALYSES OF WATER FROM WELLS AND SPRINGS

Map No.	Bicarbonate HCO_3	Sulfate SO_4	Chloride Cl	Fluoride F	Nitrate NO_3	Total Solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Noncarbonate	Specific Conductance Micromhos at 25°C	Percent Sodium
W1	201	31	10	0.4	0.0		167	2	389	
W2	202	42	28	0.2	3.9		170	4	469	33
W3	303	487	16	0.5	0.8		540	292	1330	31
W4	463	594	36			1350				
W5	196	681	9	0.3	0.1		375	214	1600	58
W6	382	846	20	0.2	3.1		58	0	2410	95
W11	261	28	32	0.2	0.0		244	30	541	15
G3	122	24	8	0.1	0.5		109	9	224	21
S2	150	8.6	11	0.2	1.9		127	4	279	15
S3	131	6.6	7	0.2	11.0		101	0	233	25
S5	210	9.1	11	0.2	7.5		168	0	369	17

TABLE 10. GEOLOGIC SECTION IN AREA 1, AND GROUND-WATER CHARACTERISTICS

UNIT	THICKNESS (in feet)	CHARACTERISTICS
Quaternary alluvium	0-50	Of local minor importance, quality good to poor, depending on source. Water in alluvium in Todilto Park would be good quality
Morrison formation		
Westwater Canyon sandstone member	184-268	Potentially good aquifer, too high in Area 1, present in bluffs along east edge of area
Recapture shale member	330-589	Cow Springs sandstone lenses may be aquifer; mostly impermeable shale
Summerville format ion	340-367	Not good aquifer, but supports several seeps
Todilto limestone	0-15	Too thin to be of importance except as an impervious layer
Entrada sandstone	220-293	Not good aquifer, present in Area 1 only in narrow belt along east edge. Only lower part of Entrada would be saturated; probably fair to good quality
Wingate sandstone	80-265	
Chinle formation	1000-1300	A few sandstone units which might be small aquifers; mostly impermeable shale. Quality is expected to be poor. Mineral content high owing to solution in shales, etc.
Shinarump conglomerate	0-50	A good aquifer in places where not cemented; quality of water should be good, especially near the recharge area
De Chelly sandstone	260-300	Possible aquifer; quality is fair where springs occur in Bonito Canyon; far-Cher from recharge area—may have dissolved greater amounts of minerals
Cutler formation	800-1000	
Quartzite	800 plus	Not an aquifer

17, fig 5), on the upper reaches of Bonito Creek, three miles south of Sawmill, serves the settlement and Tribal sawmill, at Sawmill. Small Navajo farms, a short distance southeast of the sump, obtain water from a good spring on the southwest bank of Bonito Creek. On the plateau, between the shallow trenches of Bonito Creek and its several tributaries, the Cutler formation is overlain by a gray residual silty soil, in which no water flows near the surface. The southern Cutler area is appreciably dissected, and only a few small seepages were noted along some of the eastward draining ravines. The water supply for Fort Defiance is obtained from the Cutler in lower Bonito Creek, and is discussed in detail elsewhere. Patches and narrow strips of alluvium along the larger creeks serve as supplementary reservoirs in this area.

To the west, north, and east of the area just described, lies another plateau, shaped like a horseshoe, open to the south, and underlain by the next younger formation, the De Chelly sandstone. On the west, a few unreliable small seepages (e.g., spring 19, fig 5) along shallow west-draining creeks provide a meager supply for Navajos and their stock. North and northeast of Sawmill, this belt seems to be nearly dry. One small spring (spring 16, fig 5) in the peculiar position of being perched nearly two-thirds of the way up the west slope of a small ravine, one-half mile north of Sawmill, yields water for a few families. The eastern part of this belt of De Chelly sandstone is a narrow, dry plain, devoid of seepages or springs. However, several intermittent creeks have cut their ravine bottoms into De Chelly sandstone through the overlying Shinarump conglomerate, and furnish a little water for livestock.

Over considerable areas, the next younger Chinle formation is composed of sandstones and conglomerates that are potential aquifers, since the cement has been dissolved in places. However, there are practically no surface seepages or springs in the area of the quadrangles, and the quality of water that has percolated through the surrounding Chinle shales is poor. There is the possibility that wells drilled into the Shinarump conglomerate on the east and northeast slopes of the Defiance uplift may strike potable water at moderate depth.

The central part of Todilto Park, Black Creek Valley, and the prolongation of the latter north of Red Lake, are situated in Chinle shales, with lenses of sandstone and pebble conglomerate. Although an intermittent stream, Black Creek nevertheless maintains numerous puddles and local channels that serve for stock watering. Water from Red Lake is used for irrigation in the valley between the lake and Fort Defiance. Most, if not all, of the water available in the valley is stored in alluvium, and in places the Nakaibito (the valley fill formation) is more than 20 feet thick along Black Creek, and 40 feet thick in Todilto Park.

On top of the Chinle formation is the thick succession of Jurassic strata that crop out on the eastern slopes of Black Creek Valley and in the walls of Todilto Park. There is a suggestion that at times some water seeps out from the Wingate sandstone, on top of the relatively impervious Chinle shales, discharging westward to Black Creek. However, the evidence is indirect, and though no actual springs or seeps were seen, it was noted that several dry washes end abruptly at the base of the Wingate bluff; this gives the impression that, at times when there is unusually heavy precipitation, water penetrates the fractured rock and issues forth at the base of the bluff into the washes. A few seepages, possibly at the west base of the Carmel-Entrada sandstone, are buried in alluvium so thick that no surface water was seen. At least two reliable springs are located at, or near, the base of the somewhat clayey Summerville formation. As they are on the updip side of the eastward-sloping beds, the volume of stored water may be appreciable. One spring (spring 12, fig 5) is one-fourth mile north of Twin Buttes Wash, the other (spring 11) is one-fourth mile southeast of The Beast.

The sandstone and shale lenses that make up the Morrison formation crop out over a relatively narrow, steep slope, and are of little importance at the surface. However, the Westwater Canyon sandstone, like the overlying Dakota (?), is a potential aquifer owing to its high porosity; if drilled, this formation may well yield substantial amounts of water.

TABLE 11. GEOLOGIC SECTION IN AREA 2, AND GROUND-WATER CHARACTERISTICS

UNIT	THICKNESS (in feet)	CHARACTERISTICS
Quaternary alluvium	0-50	Of local minor importance; no large reserves of ground water, but will supply small wells in washes; generally poor quality
Terraces, pediments, and landslide areas	0-50	Poor aquifers, limited reserves
Tohatchi formation	1350	Not an aquifer; occurs only beneath Chuska Mountain
Menefee formation	2300	A few relatively thin and discontinuous sandstone lenses; quality of water poor; fairly high in mineral content owing to contact with shales; before deepening, Twin Lakes well[1] obtained some water from Menefee
Point Lookout sandstone	0.365	One of best potential aquifers in the area north and west of Mexican Springs and Tohatchi; quality is fair at Tohatchi—water is hard
Crevasse Canyon formation	430-700	Generally poor; contains one good aquifer, the Dalton sandstone member, 75 to 100 feet thick; quality apparently poor; before deepening, the Twin Lakes well penetrated this formation
Gallup sandstone	100-400	Good aquifer for area south and west of Mexican Springs. One unit in north breaks into three sandstones to south; quality is fair; Twin Lakes well, after deepening, penetrated the Gallup
Mancos shale	630-750	Not an aquifer, impermeable shale
Dakota (?) sandstone	218-253	Possible aquifer, sandstone units up to 80 feet thick; quality should be fair in Area 2 because the west edge of the area is the edge of the outcrop belt of Dakota (?). Toward east edge of Area 2 the water may have dissolved considerable quantities of minerals

1. Twin Lakes well; quality data obtained from files of U.S. Geological Survey Groundwater Branch, Holbrook, Arizona.

A comparison of the above compilation with the geologic map (pl 1, in Pocket) shows that in Area 2 (underlain by the Menefee formation, except for the Manuelito Plateau) the uppermost aquifer consists of the Point Lookout sandstone, which is absent in the southern part of the area. The east-dipping Point Lookout sandstone has its recharge area along the west edge of Chuska Mountain and rapidly diminishes in thickness and pinches out south of Crevasse Canyon, so that it is absent beneath the area south and west of Mexican Springs. It lies about 1,275 feet below the surface at Tohatchi, and should be slightly deeper near Mexican Springs.

The next possible aquifer is the Dalton member of the Crevasse Canyon formation, which lies from 135 to 550 feet beneath the Point Lookout sandstone. In a well at Twin Lakes, 2 miles beyond the southern edge of the area, water was originally obtained, probably from this horizon, but the quality was poor and the well was deepened. This, in all likelihood, is the shallowest aquifer in the area south and west of Mexican Springs. The Gallup sandstone, the next aquifer, lies from 80 to 210 feet below the Dalton sandstone. The Twin Lakes well, after deepening, penetrated the Gallup. The water quality was fair. Several small seeps occur on the plateau at the base of sandstone beds of the Gallup.

Except on the Manuelito Plateau, it is doubtful whether it will ever be economic to drill the additional 600 to 700 feet through the thick Mancos shale to deeper horizons such as the Dakota (?) sandstone.

Chuska Mountain (Area 3) is underlain by upwards of 1,000 feet of crossbedded, medium-grained sandstone, which provides an excellent reservoir for the above-average precipitation which falls upon this high (9,000 ft) plateau. Furthermore, the mapped portion of the plateau is dotted with more than 100 small lakes, which are prevented by day and muck bottoms from draining quickly into the underlying porous sandstone. They provide a gradual and fairly constant recharge to the water table. This is evidenced by the rather constant minimum flow of the streams draining the western edge of the plateau, which are fed by springs near the base of the sandstone (fig 6).

The base of the Chuska sandstone lies at 8,000 to 8,100 feet along the western edge of the plateau, and at a slightly higher elevation along the eastern edge. Consequently, although there are several good springs flowing out beneath the eastern escarpment, the greater number of the springs feed the streams on the western side. Probably the best possibility for development of constant supplies of good water for domestic purposes lies in this area along the western edge, where only a small part of the emerging water is utilized at the present time. A series of earth-fill dams at the gaps in the Dakota (?) sandstone cuesta would furnish constant and considerable supplies of domestic and stock water, and might even be sufficient for some expansion of irrigation.

QUALITY OF WATER

During the course of the investigation nine water samples were collected. Five of the samples were collected from wells, one sample from a stream below the base of the Chuska sandstone, and three samples from springs near the base of the same formation. The laboratory work was performed by the U. S. Geological Survey, Quality of Water Branch, Albuquerque, New Mexico. A tenth water analysis was obtained from records maintained by the Bureau of Indian Affairs. All analyses in Table 9 report the mineral content in parts per million by weight (ppm).

The mineral constituents of ground water are obtained by solution from the rocks through which the water passes. The concentrations are dependent on the solubility of minerals in the rocks and the time the water is in contact with those minerals.

The concentrations of the various minerals affect the water's value for certain uses. The constituents will be discussed in the order in which they appear in Table 9. Silica, found in all ground waters, is significant only in boiler-water use, where it forms boiler scale. In concentrations normally found in ground-water supplies it has no effect on use for domestic, livestock, or irrigation purposes. Calcium and magnesium are responsible for most of the hardness of water. Nearly all ground waters contain small amounts of both, though some waters from limestone or gypsum contain greater amounts of calcium. Sodium and potassium are usually reported together. The proportion of sodium usually is much greater than the proportion of potassium. Sodium is important in the use of water for irrigation. When the percent sodium (the ratio of the chemical equivalents of sodium to the sum of the equivalents of calcium, magnesium, sodium and potassium) exceeds 50 to 60 it is usually responsible for the formation of "black alkali," and soils may become sticky and unworkable.

Bicarbonate is due to an excess of carbonate ions in solution when ground waters contain dissolved carbon dioxide.

Sulfate is found in low concentrations in nearly all ground waters, but in higher concentrations in water passing through gypsiferous beds. High sulfate water usually has a noticeable taste and may have a laxative effect on persons having a low sulfate tolerance. Chlorides, such as sodium chloride or common salt, are in low concentrations in waters in this area and have no effect on its use. Fluorides are present in most waters obtained from rocks, with concentrations ordinarily running higher in water from rocks of volcanic types. Fluorides have been publicized in recent years for the effect on dental enamel. According to publications of the American Water Works Association and the Public Health Service, a concentration up to 1.0 ppm is reported to be desirable for the formation of durable enamel; when present in *excess* of 1.5 to 2.0 ppm in drinking water of children, it is reported to be responsible for staining of the enamel, a condition known as mottled teeth. Again according to the publications of the American Water Works Association, water having concentrations in excess of 44 ppm nitrates has been reported to be undesirable, if not actually harmful, when used in the preparation of formulas for infants.

Hardness is reported in ppm of $CaCO_3$, usually being computed from the calcium and magnesium concentrations. Hardness is a measure of soap requirement for laundry or household purposes. Hard water also will form a scale in hot-water pipe, cooking utensils, and similar appliances, owing to the decreased solubility of the calcium salts at higher temperatures.

The specific conductance is a measure of the ability of the water to conduct an electric current. It is dependent upon the concentrations and also upon the solubilities of the various minerals. It is a rough indicator of the concentration of total dissolved solids in the water.

The water samples collected from wells Nos 3, 4, and 5 exhibit high sulfate and high specific conductance values. Such water would be unpleasant to the taste not accustomed to it and could have an undesirable physiological effect. Regular users of the water normally will build up a tolerance. By comparison, U. S. Public Health Service drinking water standards for interstate carriers limit the total solids to 1,000 ppm under maximum conditions and limit the sulfates to 250 ppm.

U. S. Department of Agriculture Circular 784 indicates that the water from No 4 would be "permissible to doubtful" for irrigation use, and that the water from No 5 would be "unsuitable" for irrigation.

The quality of water with reference to the geologic source has been noted in Tables 10 and 11.

OCCURRENCE AND GENERAL PRINCIPLES

Ground water in Tohatchi and Fort Defiance quadrangles is obtained from rocks ranging in age from the consolidated sediment of Permian age to the unconsolidated alluvium of Recent age. In consolidated formations, the water generally is contained in the joint cracks, bedding planes, solution channels, and interstices which have not been filled by cementing minerals. In unconsolidated formations, such as sands and gravels, water is contained in the pore spaces between the grains of sand, silt, or other particles making up the formation.

Any formation which is water-bearing and sufficiently permeable to yield water to wells is known as an aquifer. Permeability is that property which permits water to move through connected pore spaces, cracks, or solution channels. Some formations such as clays and shales may have a high percentage of pore spaces containing water, but also may have a very low permeability, owing to lack of connection between the pore spaces. Formations of this class will not yield water to wells, or will yield water at such a low rate as to make the very poorest of wells. The measure of the capacity of an aquifer to transmit water is its coefficient of transmissibility, which is defined as the gallons per day that will pass through a vertical strip of aquifer 1 foot wide under a gradient of 1 foot per foot.

ORIGIN AND MOVEMENT

Most of the water reaching the earth's surface as rain and snow runs off to streams, evaporates from the surface, or is transpired by vegetation. A small portion of it percolates downward through the interstices in the rocks until it reaches the water table, below which all the pore spaces are filled with water. This addition to the ground-water supply is commonly referred to as recharge. The water within an aquifer is in the process of moving from an area of recharge to an area of natural discharge. Natural discharge may occur as springs or seepage to streams or lakes, as evaporation where the water table is within capillary range of the surface, and as transpiration from plants.

WATER-TABLE AND ARTESIAN CONDITIONS

Where the saturated rocks are not confined by an overlying impermeable bed, the aquifer is said to be under water-table conditions. The upper limit of the zone of saturation, represented by the surface connecting the water levels in wells, is called the water table. The shape of the water table is generally a subdued replica of the topography. The slope of the water table at any point is known as the hydraulic gradient. Ground water moves down gradient in response to gravity.

Where an aquifer is confined between impermeable beds it is under artesian conditions. Water in the pore spaces will be under artesian or hydrostatic pressure. In wells penetrating such a formation, the water level will rise above the top of the water-bearing formation. Such wells are known as artesian wells, whether or not they flow at the surface. The imaginary surface connecting the water levels in artesian wells is known as the piezometric surface. Where the piezometric surface is above the ground, wells will flow at the surface.

RECHARGE IN THE AREA

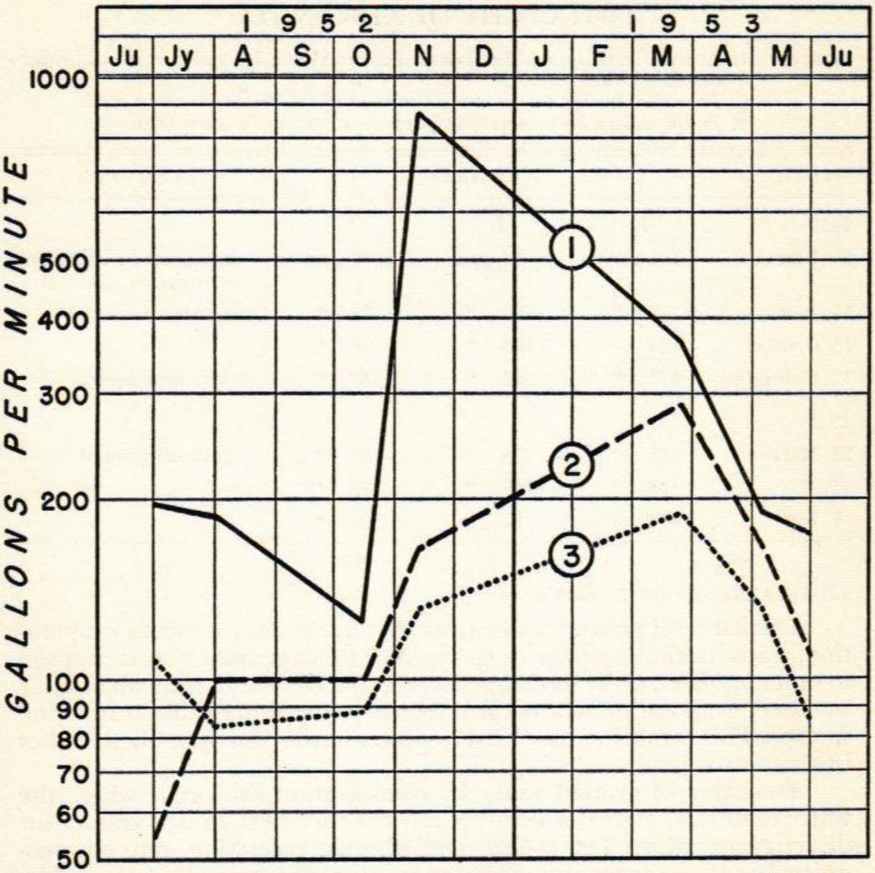
It is generally accepted that a very small proportion of the annual precipitation in semiarid climates finds its way as recharge to the groundwater reservoir. Most of the water is lost by evaporation from the soil and by transpiration. Normally, the high mountain slopes are too steep to allow much infiltration. The runoff in the washes may percolate into the alluvial fill and move down gradient as underflow until it is discharged by evapotranspiration or until it becomes recharge to permeable beds crossed by the arroyos.

The flat-lying Chuska Plateau is an exception to the general rule that runoff from high mountain areas accounts for much of the precipitation. On the plateau, surface water collects in numerous depressions in the sandy material overlying the Chuska sandstone cap rock of the plateau. Part of the water from these small lakes may escape by evaporation, but it is believed that a considerable proportion percolates downward into the sandstone until it encounters the main water table. Some of this water reappears as seeps and springs near the base of the Chuska sandstone in the outcrop areas below the edge of the plateau. This surface flow disappears in the bottoms of the various washes and much of it is probably discharged by evapotranspiration.

Where the westerly-flowing streams, such as those tributary to Todilto Wash (see fig 6 for flow of these streams), cross Cretaceous beds, some of the surface flow and underflow may be recharged to the permeable beds. The total quantity of recharge to these beds probably is small, since the exposures are not wide and many slopes are steep.

Some of the ground water in the Chuska sandstone may percolate directly into the upturned edges of the underlying Cretaceous beds.

Since insufficient data are at hand to estimate the quantity of water which enters the recharge area of the Chuska sandstone, it is impractical to estimate the quantity which may be discharging from the Chuska directly into the underlying beds; however, the quantity is believed to be great.



WEIR MEASUREMENTS ON THREE PERENNIAL STREAMS EAST OF TODILTO PARK (SEE FIG 5 FOR LOCATION).

Figure 6

Recharge in other parts of the two quadrangles probably occurs only at times of above-normal precipitation and then only as a result of sustained surface flow across permeable beds. Some continuous recharge to the Nakaibito alluvium may occur in Todilto Park, where several perennial streams heading in Chuska Mountain cross the park.

Gaging stations set up at three points, two on different forks of Todilto Wash and one on Red Willow Wash (see fig 5), give an idea of the perennial flow of these streams (fig 6) which are derived from springs at the base of the Chuska sandstone:

TABLE 12. WEIR MEASUREMENTS MADE DURING 1952-3 ON THREE PERENNIAL STREAMS IN TOHATCHI QUADRANGLE

Stations: 1. At road crossing, middle fork of Todilto Wash, 1¼ miles north of bridge on main road.
2. At road crossing, a quarter of a mile north of bridge on main road.
3. Below bridge on road crossing near head of Red Willow Wash.

Dates	Stations			Comments
1952	1.	2.	3.	
30 June	196 gpm	54 gpm	106 gpm	measured in irrigation diversion ditch at 1
31 July	188 "	100 "	83.5 "	muddy at 1 & 2
13 October	124 "	100 "	88.7 "	
12 November	873 "	165 "	130 "	after first snow
1953				
25 March	361 "	288 "	188 "	snow on ground
5 May	188 "	165 "	130 "	
1 June	172 "	83.5 "	106 "	

DISCHARGE IN THE AREA

Discharge of ground water from an aquifer may occur as evaporation, transpiration, seepage or spring flow to lakes and streams, seepage to other aquifers, or by discharge from wells. Discharge from an aquifer by direct evaporation will occur only where the water table is near the surface. This condition may exist in places in the alluvium-filled washes in these two quadrangles.

Discharge of ground water by transpiration can occur where the water table is at a greater depth below the surface than is necessary for direct evaporation. The root system of some vegetation, notably mesquite, has been reported to reach more than 40 feet to the water table. The largest loss by transpiration occurs from the plants and trees growing in the canyons and washes, where the source usually is ground water in the shallow alluvium.

Seepage or spring flow occurs normally near the base of an aquifer where the aquifer is exposed at the contact with an impermeable bed. This condition is exhibited by the springs (Nos. 4, 5, 6; fig 5) near the base of the Chuska sandstone, where it is underlain by impervious Menefee or Tohatchi shale.

Seepage to other aquifers possibly accounts for much of the water discharged from the Chuska sandstone. Seepage to adjacent beds is also a factor in the discharge from aquifers in the alluvium, where the alluvium overlies permeable beds of older rocks. Seeps and springs likewise occur in alluvium, where fine-grained sediments of silt or clay act as a subsurface barrier to force the underflow to the surface. Springs also may occur where water from an artesian aquifer forces its way through an overlying impermeable bed to the surface. The springs reported to have existed in Bonito Canyon in 1948 (Halpenny et al., 1949) may have been of this type. In 1953 no *evidence* other than saturated alluvial fill and swampy areas was found in the vicinity of the spring reported to have yielded as high as 315 gpm in 1948.

Discharge from wells in these quadrangles has not yet been sufficient to cause a major upset in nature's balance between recharge and discharge. Under natural conditions, a ground-water reservoir will approach or attain a state of equilibrium with natural recharge balanced by natural discharge. The water table or piezometric surface has a general slope from recharge area to discharge area, which occurs at a lower altitude. Discharge from wells by pumping is accompanied by a lowering of the water table into an inverted "cone of depression" with the well at the apex. At the start of well discharge, water is obtained from storage in the immediate vicinity of the well. As discharge continues, the effect of pumping reaches out farther and farther until it intercepts an area of natural discharge or an area where additional recharge can be induced as a result of lowering the water table in the recharge area. If neither natural discharge is intercepted nor additional recharge induced, the water must continue to come from storage and the water levels will continue to decline, although at an ever-decreasing rate. On a practical basis, none of the wells within this area discharges water at a sufficiently high rate for the effect to be observed beyond a local area. Long-term records of water levels and pumpage were not available for this area.

There is considerable evidence to indicate that during the last 50 years the available water and discharge in the area has decreased somewhat. In 1892, Bonito Creek is reported (Gregory, 1916, p 91) to have flowed .87 second-feet (390 gpm) at low water, and Buell Park Wash .05 second-feet. In March, April, and July, 1948 the discharge of Bonito Spring in Bonito Creek was measured three times, giving 265 gpm, 315 gpm, and 250 gpm (Halpenny et al., 1949, p 8). Gregory stated that Black Creek itself was a perennial stream above Red Lake; engineers of the Indian Service found the runoff to be 33,328 acre-feet per year. Below Red Lake, Black Creek was (Gregory, 1916, p 91), and still is, an intermittent stream. Figueredo Wash below Mexican Springs flowed 30 gpm at low water, being perennial for over 5 miles in 1911. These streams were all intermittent in 1952 and 1953, seldom flowing for more than a few weeks or months at a time, except in their uppermost reaches.

USE OF WATER IN THE AREA

Principal uses of ground water in the quadrangles is for domestic purposes and watering livestock. Some ground water is used for boiler water in the power plants at Tohatchi and Fort Defiance, also for laundry purposes in both communities. Scarcity of local domestic supply necessitates truck or wagon transportation in barrels from springs and wells to the hogans scattered throughout the area.

Use of ground water for irrigation is on a very small scale in the upper reaches of Todilto Wash, where the flow of several springs is diverted to cultivated areas. Raising of the dam at the outlet to Red Lake during 1952-3 may eventually permit enlargement of the area under irrigation in Black Creek Valley. Several years ago, some ground water may have been pumped from wells and put to use in the Mexican Springs Demonstration Area, but no confirmation of this was obtained. It is reported that in the area east of Tohatchi quadrangle the discharge of several flowing wells has been put to irrigational use.

Geology

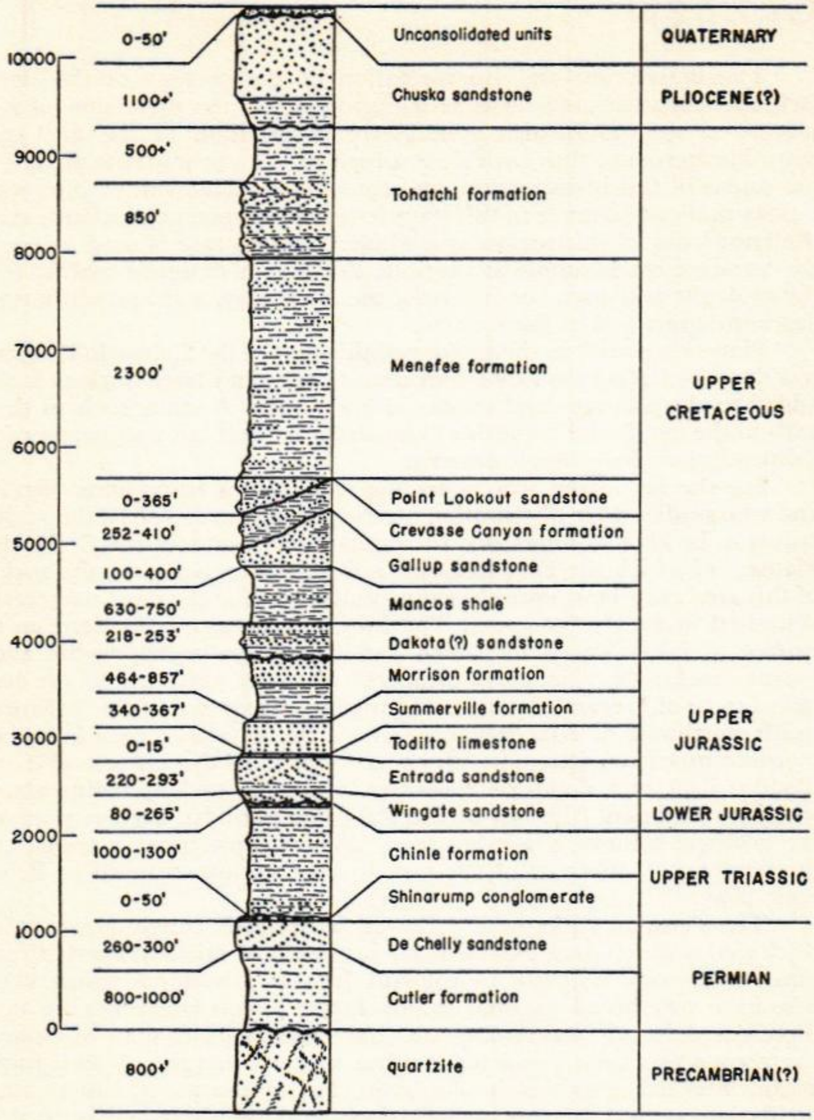
The description and interpretation of the geology of the Fort Defiance-Tohatchi area serve as background for the discussion of resources as well as furnish a necessary explanation of the geologic map. Furthermore, they provide a record of the observations made in the course of this investigation, and constitute a statement of interpretations that can be made at this stage in the development of science and the knowledge of this region as a whole. Though care is used to keep the terminology as simple as possible, this text is designed mainly for the geologist and engineer. To assist the lay reader, a glossary of terms has been appended to the volume.

Pioneering work in the geology of this part of the Colorado Plateau was done by Gregory nearly a half century ago, and later workers have added to the accuracy and extent of knowledge. A study such as this adds to the detail and breadth of knowledge as well as to refinement in delineation of the geologic pattern.

For the lay reader who notes the sequence of formations (fig 7) and who studies their distribution on the geologic map (pl 1), the main points to be kept in mind are: In common with most of the Colorado Plateau, of which the Fort Defiance-Tohatchi area is a part, the rocks of this area are almost entirely sedimentary, and for the most part were deposited in nearly fiat strata. The initial layers were deposited on a surface of fairly low relief which had formed on metamorphic and igneous rocks, the "basement complex" of many writers, and are believed to be of Precambrian age. This surface is exposed in the Defiance uplift northwest of Fort Defiance, where the basement rock is metamorphic quartzite. Quartzite also was reached in the oil test well in Todilto Park at a depth of 2,440 feet. Since the earliest sedimentary rocks are Permian (the last of the Paleozoic periods), a great part of the geologic column is missing from this area, presumably owing to the tendency of this part of the earth's crust to push upward in Paleozoic time.

The Permian rocks were followed by Triassic conglomerate and thick shales which once extended for hundreds of miles in every direction. These were followed by colorful Jurassic sandstones which likewise have very broad regional extent. Lower Cretaceous rocks are not represented, but thousands of feet of drab sandstone and shale of Upper Cretaceous age were deposited on the western margin of San Juan Basin. The sea remained in the basin, but at the margin there was oscillation, so that the sea encroached on land and deposited beds; the land deposits encroached on those of the sea, providing what the geologist calls transgressive and regressive overlap.

With the close of Upper Cretaceous time, the crust of the earth was disturbed, with resulting differential uplift and depression. Rocks in Fort Defiance quadrangle were pushed upward; those in Tohatchi quadrangle were relatively depressed (see fig 8). All of these rocks were now above the sea, and those lifted highest were subjected to the most vigorous erosion, which in time reduced all the region to a surface of



GENERALIZED STRATIGRAPHIC COLUMN FOR FORT DEFIANCE AND TOHATCHI QUADRANGLES.

Figure 7

low relief. Evidently in late Tertiary time this surface was covered by the Chuska sandstone through which volcanic eruptions broke. Probably some erosion preceded a part of the volcanic activity. Renewed uplift caused most of the Chuska formation in turn to be eroded; only remnants here and there, the largest of which makes up the summit of Chuska Mountain, attest to the former wide extent of this formation. Erosion has continued to the present time; climatic changes for the most part dictate whether a valley will fill with sediment from high areas or whether the valley fill itself will be eroded away. With few exceptions, removal of valley fill is now in process in the area.

The sedimentary rocks throughout the 11,000 feet of section are almost wholly elastic. Therefore, rather precise terms must be used in the descriptions in order to convey distinctions which are of economic as well as scientific importance. The table below (modified from Wentworth, 1922) gives the actual range of grain-size for each descriptive term that is used.

TABLE 13. CLASTIC GRAIN-SIZE CLASSIFICATION

Rock name	Descriptive adjectives	Size range Millimeters	Inches
Conglomerate	boulder	over 265	over 10½
	cobble	64-265	2½-10½
	pebble	4-64	¼ - 2½
Sandstone	granule	2-4	⅛ - ¼
	very coarse (grit)	1-2	1/16 - ⅛
	coarse	.5-1	1/32 - 1/16
	medium	.25-.5	1/64 - 1/32
	fine	.125-.25	1/128 - 1/64
	very fine	.062-.125	1/256 - 1/128
Siltstone		.004-.062	less than 1/256
Shale and mudstone		less than .004	

For rocks in which there is a notable range in grain-size, descriptive adjectives are used; the adjective indicates the lesser component:

sandy conglomerate
conglomeratic sandstone
silty sandstone
sandy siltstone
shaly sil tstone
silty shale

Terms indicating the thickness of beds are essentially those of McKee and Weir (1953). Inclined bedding within a layer is called cross-stratification or, if on a fine scale, crosslamination.

Terms denoting color follow closely the standards established by the Rock-Color Chart Committee of the National Research Council (Goddard, 1948). Color symbols follow the color terms used.

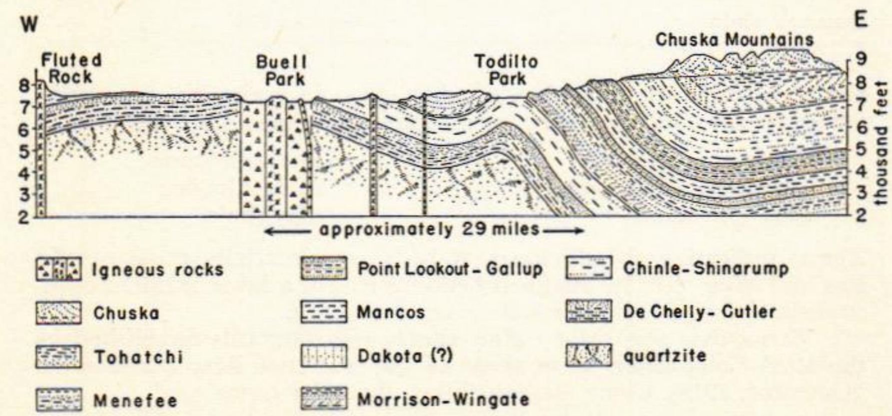
TABLE 14. CLASSIFICATION OF BED-THICKNESS AND SPLITTING PROPERTY

DESCRIPTIVE TERMS	THICKNESS MILLIMETERS	THICKNESS INCHES	SPLITTING PROPERTY
Very thick-bedded	over 1200	over 48	massive
Thick-bedded	1200-600	48- 24	blocky
Thin-bedded	600.50	24- 2	slabby
Very thin-bedded	50-10	2-.5	flaggy
Laminated	10.2	.5-.08	shaly or platy
Thinly laminated	2 or less	.08 or less	papery or fissile

PRECAMBRIAN (?) SYSTEM

The oldest rock in the Fort Defiance-Tohatchi area is quartzite found in two small exposures on Bonito Creek and Blue Canyon Wash 2½ miles and 3½ miles, respectively, northwest of Fort Defiance. The base of the formation is not exposed and the top is a somewhat irregular erosion surface showing angular unconformity with the overlying Cutler formation (pl 4-A). Key beds in the quartzite are lacking, and the combined thickness in the two outcrops can only be estimated at about 800 feet.

In both canyons the quartzite is a gray to dark-purplish, hard, well-bedded, and intensely fractured rock in which there are thin lenses of siliceous pebble conglomerates and siliceous slate. The beds dip about 25° SW. Fossils are lacking, but micaceous bedding planes commonly show ripple marks, mud cracks, and current lineation.



DIAGRAMMATIC EAST-WEST SECTION THROUGH FORT DEFIANCE AND TOHATCHI QUADRANGLES.

Figure 8

Under the microscope, thin slices of the quartzite show angular grains of quartz in a matrix or cement of minute scales and blebs of colorless sericite, together with very fine-grained secondary quartz. Many quartz grains have been partly replaced by the sericitic matrix; minute flakes of mica indent the elastic grains. Accessory minerals (in decreasing order of abundance) are magnetite, zircon, colorless garnet, and tourmaline.

Gregory (1917, pp 17-18) noted these exposures of quartzite and interpreted them as of probable Precambrian age in view of the degree of metamorphism and the lack of similar quartzite in any relatively nearby Paleozoic section, in addition to their unconformable relation to the overlying Permian. Because of the lack of shearing and granitoid intrusive rock, the preservation of sedimentary features, and the similarity to late Precambrian quartzite in the Grand Canyon, a late Precambrian age might reasonably be assigned to this rock.

PERMIAN SYSTEM

CUTLER FORMATION

The Cutler formation crops out in one large, elliptical area that extends from Buell Park and Sawmill southward to Bonito Canyon and to the southern border of Fort Defiance quadrangle, west of that canyon. This part of the Defiance plateau has been uplifted to the greatest extent, and erosion has uncovered the oldest stratigraphic units.

The base of the Cutler formation is exposed only at the two canyons that show the pre-Permian quartzite. The contact rises about 50 feet above the creek bed in Blue Canyon Wash, and the flat-lying strata of the Cutler formation transgress over this "hill" (see pl 3-A). At the contact, vertical fractures in the quartzite are filled to a depth of 6 feet with red and greenish-gray material, which apparently seeped in as a mud from above. The base of the Cutler is a pebble bed, composed of a miniature pavement of gray quartzite pebbles, about 1 inch across. Locally, the basal beds of the Cutler formation contain considerable quantities of quartzite debris. The quartzite at Bonito Canyon is overlain by 3 feet of maroon shale, cut into by sandstone channels, 2 to 3 feet wide. Quartzite pebbles, up to one-half inch in diameter, are scattered through the lower 2 feet of the Cutler shale, and single quartzite pebbles, several inches across, were found in outcrops of the formation as much as a half mile from the two quartzite outcrops.

The top of the Cutler must be drawn somewhat arbitrarily. In the upper Cutler formation, sandstone increases in proportion to shale, but a brick-red color remains distinctive. Dark reddish-brown shale lenses, 2 to 8 feet thick, decrease upward in number and thickness, and the top of the Cutler formation has been drawn at the top of the highest shale zone, though it is not known how closely this lithologic boundary corresponds with a time line.

In an east-west section from Bonito Canyon to the eastern rim of the De Chelly sandstone, the Cutler formation is 800 feet thick. A well at Sawmill struck quartzite at a depth of 798 feet below the surface, and if the base of the De Chelly sandstone is reconstructed to pass over Sawmill, an estimated thickness for the Cutler formation of about 1,000 feet is suggested. Elsewhere, the formation may be even thicker, but the base is not exposed.

The lower part of the Cutler consists of brick-red, thin- to thick-bedded, poorly cemented, rarely crossbedded, arenaceous siltstones, shales, and sandstones. Gray sandstone beds, 2 to 4 feet thick, and thinner pebble-conglomerate lenses, are sparingly present in most of the larger outcrops. Pink, gray, or reddish pebbles of fine-grained sandstone, a fraction of an inch to 4 inches across, are held by a calcareous, locally coarse, cement; calcite seems to be the most common cementing mineral in the lower Cutler formation. Joint veneers and large crystal clusters in fractured zones may exhibit nicely terminated calcite crystals.

Crossbedding in the lower Cutler formation occurs only on a small scale. The layers that bevel one another are rarely more than 1 inch thick, and resemble each other so closely in grain-size, color, and manner of weathering, that outcrops of these rocks give the appearance of essentially parallel-bedded, homogeneous silty sandstones, or siltstones. Mud cracks and ripple marks, as well as current lineation (Stokes, 1947), were observed occasionally.

The upper portion of the Cutler formation consists of a much larger proportion of pale-brick to salmon-colored, crossbedded sandstones, with subordinate brown or maroon shale lenses. Thicknesses of 280, 228, and 192 feet were measured, but, as stated above, neither the base nor the top of the division can be accurately correlated from one outcrop to another.

Under the microscope, arenaceous phases of the Cutler formation show quartz grains, rarely over 0.1 mm in diameter, a moderate amount of feldspar, especially microline, and a brownish groundmass of sericite and carbonate. Accessory minerals are magnetite, zircon, and tourmaline.

Fragments of *Walchia* (a primitive conifer) have been found in the lower Cutler formation "3 miles west of Fort Defiance" (Gregory, 1917, p 31).

The lower Cutler formation is well exposed in several western tributaries of Bonito Canyon, but in the central part of the Sawmill upland, a gray residual soil covers the formation. The upper Cutler sandstone sequence is exposed on the east side of Bonito Canyon, on the southeast wall of Buell Park, and on the eastern slopes of Piney Hill. Where the relief is subdued, the rock disintegrates to a pink, sandy soil.

The Cutler formation is interpreted as a flood-plain deposit that formed to the north of a shallow sea that advanced slowly northward in middle Permian time.

Present correlation in the Colorado Plateau places the Cutler formation in the Leonard series of the Permian system (Read, 1951, pp 82, 83). Formerly this formation was thought to be the equivalent of the Moenkopi (Gregory, 1917, pp 27-29). For a discussion of the terminology of the various formations, see Cross and Howe (1905), Baker and Reeside (1929), and Dane (1935). In other parts of northern Arizona, the formation called Supai is about equivalent to the Cutler.

DE CHELLY SANDSTONE

The De Chelly sandstone surrounds, as a nearly continuous rim, the oval area underlain by the Cutler formation. On the east flank of the Defiance uplift, its width of outcrop is narrowed by the overlying Shinarump conglomerate, but southwest of Sawmill, the conglomerate has been eroded from a considerable area; the De Chelly sandstone here underlies a large, forested plateau. In the extreme northwest corner of Fort Defiance quadrangle, the De Chelly sandstone is exposed in the upper end of Monument Canyon. Detached areas of the formation appear in the ravines that drain the east flank of the Defiance uplift.

The base of the De Chelly sandstone was drawn, somewhat arbitrarily, above the highest shaly zone in the upper Cutler sandstone sequence. The top, however, is the sharp contact with the Shinarump conglomerate, an erosion surface well exposed in many prominent cliffs.

In three measured sections the De Chelly sandstone has a thickness of 259, 281, and 299 feet. Heald (in Gregory, 1917, p 32) measured 263 feet at Bonito Canyon, but obtained larger figures at Buell Park. Probably sandstones of the upper Cutler formation were included here with the De Chelly sandstone. At Canyon De Chelly, however, the formation is much thicker.

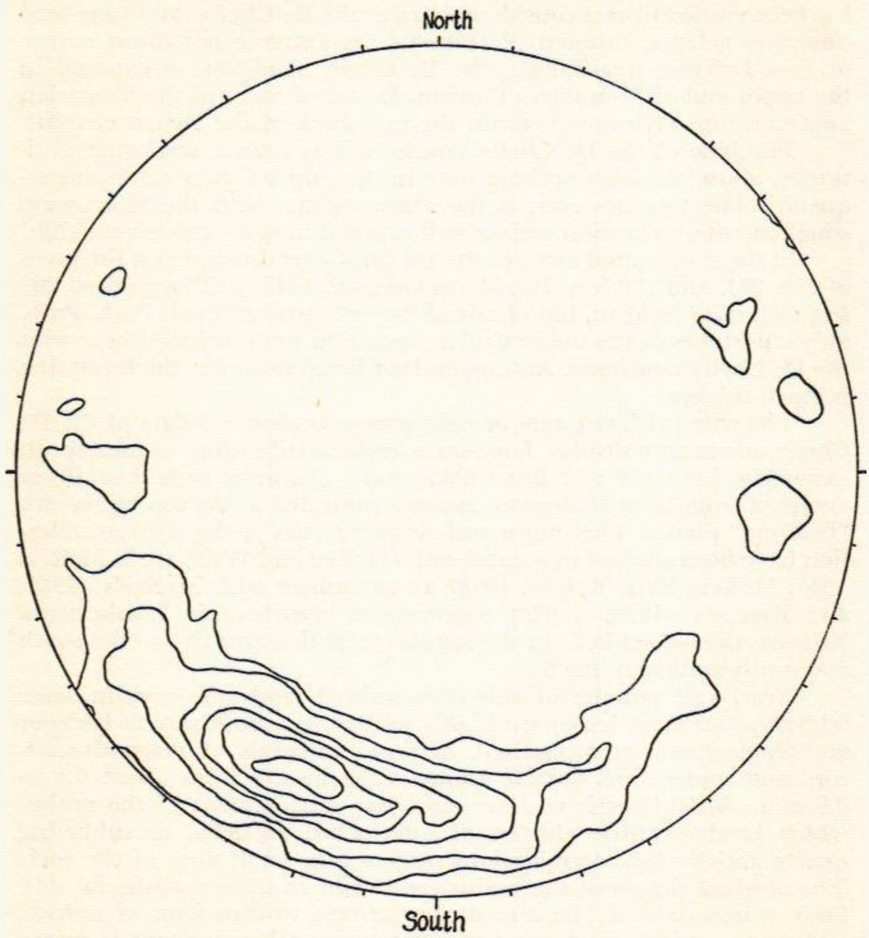
The pale brick-red, tan, or pale-orange sandstone ledges of the De Chelly formation display large-scale cross-stratification in nearly all exposures. Layers, 2 to 6 feet thick, consist of foreset beds that dip at angles of from 15 to 30 degrees, and are truncated at the top by smooth "bedding" planes. The origin and characteristics of the cross-stratification have been studied in great detail (McKee and Weir, 1953; McKee, 1945; McKee, 1934; Reiche, 1938). In agreement with McKee's (1934) and Reiche's (1938, p 920) observations elsewhere in northeastern Arizona, the foreset beds in the sandstone in this area dip to the south and south-southwest (fig 9).

Nearly all samples of this even-grained sandstone contain some feldspar, and some lenses are highly feldspathic. Both potash feldspar and plagioclase were recognized. Accessory minerals are magnetite, zircon, and tourmaline. Quartz grains range in size from about 0.1 to 0.5 mm. All thinsections show secondary enlargement of the grains, which produces little clusters of interlocked anhedra, or subhedral quartz grains whose terminations project into small vugs of the rock. The original shapes of the grains are shown in most samples by thin films of iron oxides. The cement is restricted to thin films of sericite, carbonate, or iron oxide, and in some places where cement is nearly absent, grains can be rubbed off the ledge without difficulty. In view of the secondary changes in the shape of so many quartz grains, the original roundness is difficult to estimate. However, the feldspar grains are well rounded, and it is thought that the quartz grains were also for the most part well rounded.

No fossils have been found in the De Chelly sandstone in this region.

The history of the De Chelly sandstone is closely related to that of the Cutler formation. According to Read (1951, p 83), the De Chelly sandstone can be considered as a shifting beach and bar deposit. As such, it lacks a constant thickness, and its time relation to the surrounding red beds is involved.

The name De Chelly sandstone was introduced by Gregory (1915; 1916; 1917, p 31). The formation, now considered to be a member of



DIRECTION AND ANGLE OF DIP OF CROSS-STRATA IN 293 OUTCROPS OF DE CHELLY SANDSTONE IN FORT DEFIANCE QUADRANGLE.

Data shown on equal-area stereographic projection, lower hemisphere. Contours are 0.3, 1, 2, 3, 4, and 5 percent. Maximum shows south-southwesterly dip of 20-25 degrees.

Figure 9

the Permian Cutler formation (Baker and Reeside, 1929, pp 1427, 1432-33, 1443, 1446), is in all essentials the equivalent of the Coconino sandstone farther west, though it may be of slightly later age than the bulk of the Coconino (Baker and Reeside, fig 12, p 1446). According to McKee (1934, p 227), the De Chelly sandstone differs from the Coconino in having a dominantly ferruginous or calcareous cement, whereas the Coconino sandstone has a siliceous cement. Locally, as at Bonito Canyon, and for several miles north of that point, the uppermost 10 feet of the De Chelly sandstone is brown, and 1 or 2 feet of brick-red shale may lie directly below the Shinarump conglomerate. According to Baker and Reeside (1929, pp 1443, 1446, fig 12), these argillaceous beds may be the top of the Cutler formation. However, the outcrops are so sporadic that they have not been distinguished from the De Chelly sandstone.

The De Chelly sandstone is currently thought to be of middle Permian (Leonard) age, even though it is unfossiliferous in the region.

UPPER TRIASSIC SERIES

SHINARUMP CONGLOMERATE

From the western border of Fort Defiance quadrangle, 7 miles southwest of Sawmill, the Shinarump conglomerate can be followed in a general northeasterly direction to a point 3 miles northwest of Sawmill, where the outcrop area splits. Because of a gentle arch extending northwest from Sawmill, the conglomerate crops out in a series of low ledges trending northwest toward the extreme northwest corner of Fort Defiance quadrangle. A second, larger outcrop zone swings eastward north of Sawmill, skirts Buell Park on the north, and thence extends southward to Fort Defiance. In this zone, the conglomerate constitutes the main bedrock formation underlying the forested slope that reaches from the Defiance Plateau to Black Creek Valley.

The base of the Shinarump conglomerate is sharply defined and rests on the De Chelly sandstone. The top has been designated as the upper surface of the conglomerate that rests on the De Chelly; the numerous lithologically similar conglomerate lenses that appear above the top have been mapped with the lower part of the Chinle formation. Thus defined, the Shinarump conglomerate in the mapped area ranges from 0 to about 35 feet thick. In some poorly exposed districts, its thickness may be greater.

The Shinarump conglomerate is composed of well-rounded to subangular pebbles of quartzite, chert, and other highly siliceous rocks, ranging in size from a small fraction of an inch to about 6 inches across. Gray, tan, and pink pebbles are most common, but black, red, yellow, and brown pebbles are locally abundant. Brown, yellow, red, and grayish silicified wood in fairly large fragments is also a common constituent. The matrix of the conglomerate consists of a fairly coarse, sharp quartz sand that may grade in size to that of the smaller pebbles.

Where vertical cliffs afford cross-sections through the conglomerate, channels filled with rather coarse rubble can be differentiated from the surrounding rock, which is a coarse sandstone with much fewer, and smaller, pebbles. Channels about 2 to 5 miles north of Fort Defiance, on the slope toward Black Creek Valley, measure 30 to 50 feet in width, and 5 to 10 feet in depth. Such channels in other parts of the Colorado Plateau are of economic importance owing to their association with uranium deposits (Bain, 1953), though they have been unproductive thus far in the Fort Defiance-Tohatchi area. That at least some of the channels were cut by swiftly flowing water, is demonstrated by an interesting outcrop in the bed of one of the many shallow ravines draining the east slope of the Defiance uplift, about 3 miles north of Fort Defiance. Here the Shinarump conglomerate is plastered over and against a vertical diff, about 6 feet high, in the underlying De Chelly sandstone. A flat bedding surface at the bottom of the cliff contains a pothole, 1 foot across, the bottom of which is filled with silicified and strongly cemented Shinarump pebbles. This flat surface again drops off into another steep face, and again the conglomerate is deposited against it. The total relief at the base of the Shinarump is about 9 feet. In other places, the relief at the base of the Shinarump amounts to 3 to 4 feet, but since key beds in the De Chelly sandstone are lacking, the actual relief at the base of the conglomerate may be considerable.

The conglomerate has been considerably silicified and leached. Accordingly, the rock is porous nearly everywhere and, even from a distance, the surfaces glisten from reflecting faces of enlarged quartz crystals and veneers of euhedral, secondary grains. It is fairly certain that many of the chert pebbles were originally composed of other rocks later replaced by silica. Chert pebbles found by C. Richard Maise at the southeast rim of Buell Park contain fusulinids, and almost certainly represent completely silicified limestone pebbles, perhaps from the Kaibab formation. Through the kindness of Clay T. Smith, the writers received another batch of very similar chert pebbles with silicified fusulinids from the Shinarump conglomerate at the Zuni Plateau. Another striking illustration of the chemical changes is indentation of pebbles. Of two adjacent pebbles, one has retained its generally convex outline, whereas the neighboring pebble has been indented by solution, so that it fits exactly onto, and partly around, the other pebble. The pebbles are not cemented to each other, and why one retained its original form, while the neighboring pebble was partly dissolved, remains a mystery.

In a gravel pit by the improved road from Fort Defiance to Sawmill, 2.9 miles north of Fort Defiance, the conglomerate is in places so completely silicified that, at the blow of a hammer, fractures penetrate smoothly through the matrix and pebbles. Yet other masses of the same rock are highly porous, with cavities over 1 inch across, coated with an aphanitic white powder, partly carbonate, partly silica, and the space between them is occupied by loose gravel in which the chert pebbles lie completely separated from the enclosing groundmass.

Northwest of Sawmill, the Shinarump conglomerate has not only *been* leached and locally silicified but, in addition, the cementing substance has been partly replaced by iron oxides (see pl 10-E). Some of the original cement may have been carbonate, which is found in the interior of some nearly black ferruginous masses. The replacement of the rock by iron oxide can convert the conglomerate into soft masses of hematite, and small test pits have been opened in this rock 4½ miles northwest of Sawmill (see fig 2).

North of Buell Park and Sawmill, the conglomerate underlies an old land surface. Here it is deeply disintegrated, but its presence is betrayed by quantities of loose chert pebbles. As they are exceptionally resistant to chemical decomposition, they remain intact in the soil and thus participate in its slow creep. They are found, therefore, many miles from known outcrops, and although this makes the mapping of the formation difficult, the pebbles help to reconstruct these ancient land surfaces.

On the basis of vertebrate remains (Camp, 1930) and abundant fossil plants (Daugherty, 1941), the Shinarump conglomerate is believed to be of late Triassic age.

Observations in one limited area do not contribute much towards the elucidation of the origin of the Shinarump conglomerate. It is generally thought to be a continental deposit that was deposited over an astonishingly large and, it seems, flat area. The scattered stream channels are the only irregularities in this siliceous blanket.

The early geologists of the Colorado Plateau area recognized above the Paleozoic rocks a series of sandstones, shales, and siltstones in which strikingly colored conglomerates occurred. To these rocks the name "Shinarump group" was given, but Gregory (1913, p 426) made a proposal, accepted by subsequent workers, that the conglomerate be considered a formation in view of its exceptionally wide distribution in the entire Colorado Plateau area.

CHINLE FORMATION

Chinle Valley, the type locality of the Chinle formation, lies 20 miles west of Fort Defiance quadrangle. From here the formation reaches the mapped area in two branches: a narrow zone along the western border of Fort Defiance quadrangle, where the lowest members of the formation form a thin wedge upon the Shinarump conglomerate, and a much larger area that includes the entire northern part of Fort Defiance quadrangle, and extends into the northwest corner of Tohatchi quadrangle. The formation underlies most of the "park" region of Todilto Park, which merges with the lowland north of Red Lake. From here it extends southward, underlying Black Creek Valley which, geologically speaking, is the counterpart, on the east side of the Defiance uplift, of Chinle Valley.

The lower contact of the Chinle formation is drawn, for the area of this report, at the top of the Shinarump conglomerate. There are, however, places where the Shinarump is so thin that the Chinle virtually rests on the De Chelly sandstone, as, for example, in outcrops near the northwestern corner of Fort Defiance quadrangle, and locally on the east slope of the Defiance uplift north of Fort Defiance. The top of the formation is a widespread disconformity, considered to be an irregular erosion surface overlain by a granule-pebble conglomerate. This is not necessarily the break between the Triassic and Jurassic systerns, although it has been so mapped. The top of the formation is completely exposed only in the creek bed on the north branch of Bowl Springs Wash, about 21/2 miles north of the main road. Just west of the "Haystacks," due east of Fort Defiance, the highest Chinle beds are exposed some 15 feet below the Wingate sandstone.

Owing to poor outcrops, low dips, and slumping on gentle slopes, accurate measurements of the thickness of the Chinle are difficult to obtain. A plane-table traverse from the Humble well in Todilto Park gave a thickness of 1,277 feet. According to Wengerd (1950, p 69), the thickness in the vicinity is 1,850 feet. The figure seems a little too high; 1,300 feet may be closer to the truth.

The Chinle formation comprises more varied types of rock than probably any other formation in the area. Clays and shales of brown, purple, reddish, green, gray, or white color are abundant. In the lower part of the formation the shales are interbedded with innumerable lenses of tan, gray, or pinkish sandstone and conglomerate. None of these lenses could be traced through the entire mapped area, but the most persistent are shown on the map by a special symbol. Pebble conglomerates form prominent cuestas in the middle Chinle formation. Some green lenses in Black Creek Valley contain many rounded pebbles of mudstone and siltstone, lying in a chloritic base, cemented by carbonate. A persistent zone of pale-greenish limestone-pellet conglomerates, mottled lavender, brown, and white, accompanies the entire outcrop area in Black Creek Valley, close to the top of the formation. The rock shows considerable chemical reconstitution, and whether it was originally a pebble conglomerate or not is uncertain.

Cross-stratification in the sandstone lenses of the Chinle differs from that in De Chelly sandstones. The packets of foreset beds in the De Chelly sandstone nearly everywhere are several feet thick, whereas, in the lower Chinle, the current-bedding consists of hundreds of lenses of fine-grained tan sand, rarely thicker than 1 or 2 inches, alternating with each other on a small scale. Larger surfaces suggest a "weaving in and out" of the lentides. Though the coarser sandstone lenses resemble closely the underlying Shinarump conglomerate in composition and texture, they are not as intensely silicified as in the Shinarump. Leaching of the rocks, however, is common. North of Buell Park, conglomerates in the lower Chinle are cavernous, and many pebbles have been partly corroded, though none seems to have been silicified. Current lineation was noted in many places in the lower Chinle sandstones, and the direction of the streaks is uniformly northwest-southeast.

Samples from arenaceous and calcareous lenses in the Chinle formation, when examined microscopically, were found to contain quartz grains measuring about 0.2 to 1 mm in diameter. As much as 10 percent of potash feldspar and plagioclase may be admixed, and small shreds of muscovite are widespread. A chlorite, close to penninite, is the cause of the green color of many sandstones and pebble conglomerates. In thinsections from a ridge in Black Creek Valley, 31/2 miles northeast of Fort Defiance, the chlorite proves to be derived from biotite (pleochroism brown to nearly black). Glauconite was sought in vain, and X-ray powder diffraction photographs of the green material show chlorite only.

Calcite cement is common in the Chinle sandstones, and is in part responsible for their easy weathering. Pellets of carbonate are present in some lower Chinle sandstones. Calcareous sandstones and chloritic calcareous conglomerates are prominently developed in the middle Chinle strata, east of Black Creek. Some of these rocks pass into coarse shell breccias in which fresh-water bivalves (clams) are intermingled with green mud pellets.

The upper Chinle shales are commonly of pink, lavender, and pale-brick color; and although they, too, contain much carbonate, its presence is somewhat overshadowed by local silicification. An interesting example is the persistent greenish-gray limestone-pellet conglomerate on the east side of Black Creek Valley. The rock is composed of very small calcite grains, locally intergrown with chalcedony, though larger calcite grains as well as elastic quartz are occasionally seen. The spaces between these larger grains are occupied by a secondary calcite generation in which chert, or chalcedonic quartz, forms numerous patches. One dissolved sample gave 18 percent of insolubles, mostly chalcedony. Another specimen, from Bowl Canyon Wash, analyzed by H. B. Wiik (Helsinki), gave the following composition:

$Si0_2$	47.30%
Al2O3	0.84%
Fe_20_3 (total iron)	0.95%
CaO	25.60%
MgO	1.68%

After solidification, these rocks were apparently fractured, and the separated pieces were recemented by disseminated chalcedony and fine-grained calcite, but the boundaries of the fragments have been blurred and partly eliminated by subsequent solution and recementation. The true history of these pellet conglomerates is difficult to unravel. Perhaps they were fresh-water limestones originally, but were modified greatly through partial solution, and recementation by silica.

The considerable chemical alteration, to which most of the sedimentary rocks of this region have been subjected, is exemplified by the shell banks in the middle Chinle. The shells are themselves composed of large crystals of calcite, and under the microscope it is seen that many of these crystals continue in identical orientation into the ground-mass of the surrounding chloritic conglomerate. Elsewhere, the calcite of the clam shells has been dissolved, and aggregates of secondary calcite, with or without chalcedony, have developed in their spaces. For this reason most of the clams are poorly preserved, and it is nearly impossible to remove a whole shell from the rock.

Silicified wood is very common in the lower Chinle formation. According to Daugherty (1941), the most common genera among the trees *are Araucarioxylon* and *Woodworthia* (primitive conifers). Altogether, 38 species of coniferous plants have been determined in the plateau area. Thousands of trunk and branch fragments strew the western slopes of Black Creek Valley and the floor of the large meadow, north and south of Fluted Rock. Close to the base of the formation, large cross-sections of tree trunks were seen north of Fort Defiance, 2½ miles north-northeast of Buell Park, and near the northwestern corner of Fort Defiance quadrangle. A trunk, 18 feet long and 14 inches in diameter, lies on a hillside about 1,000 feet southwest of the west end of Fluted Rock, just outside Fort Defiance quadrangle. Many additional large tree fragments, as well as smaller ones, lie nearby. Commonly the color of the wood in this area is mottled grayish-brown. Ivory-colored and white wood weathers out in purple and gray clay on the southwest-facing slope, 2 miles northeast of Buell Park. Red wood is found in places on the west slope of Black Creek Valley, 2-3 miles northeast of Fort Defiance.

Fossil fresh-water bivalves were found in several places in the middle Chinle. One and a half to 3 miles northeast of Fort Defiance, several lenses of gray sandstone and pebble conglomerate contain the clam banks previously mentioned. They are best developed on the eastern crest of the ridge, about 3 miles from Fort Defiance. Closely packed unionid shells build up a lens, 5 feet thick and several hundred feet long, and several smaller lenses with fewer shells accompany this farther north. Two species of fresh-water pelecypods are recognized in the shell banks. They appear to be identical with two species illustrated by Meek (in Cope, 1877, p1 23, figs 2, 2a, 8, 8a, 9, 9a). One of these Meek named *Unio cristonensis;* the other he designated as *Unio sp.,* and this form was described only in the discussion of *U. cristonensis* (Meek, in Cope, 1875, pp 83-84).

Currently, most of the North American Triassic pelecypods of this general aspect are placed in the genus *Diplodon,* a genus known from living species which are confined to fresh waters of the southern hemisphere, in Africa and South America. The reference of these species to *Diplodon* seems highly dubious. They show no trace of the radial markings considered a criterion of the genus, and show differences in the hinge structure which seem adequate to indicate that these two species actually belong to different genera. Description and illustration of these forms is delayed pending a satisfactory solution of their taxonomic position among the forty-odd genera into which the shells, placed in *Unio* in Meek's day, are currently divided.

A similar deposit was found in red Chinle clay, about $2^1/_8$ miles northeast of Fort Defiance, where it underlies a long, narrow north-south trending ridge, west of the one that is held up by the greenish-pink limestone-pellet conglomerate. In the red clay single bivalves lie about as molds, and do not build up solid banks. Cleaning and preparation of these shells for accurate identification is tedious. At this writing, specifically identifiable individuals have not been found, but the collected material is voluminous, and work on the fossils continues. In all outward aspects the shells resemble closely those found in other localities in the Chinle formation.

The extensive mud and sandstone deposits of the Chinle formation are believed to be the record of a prolonged period of accumulation of fine debris over a very large plain that covered most of the Colorado Plateau in late Triassic time. There is no evidence that any of the typical Chinle sediments are of marine origin, but much of the calcareous material may have accumulated in fresh-water basins. McKee (1951, p 91) thinks that most of the mud and sand was brought in from a newly raised area to the south. The striking variability of color in the Chinle sediments, the peculiar manner in which the clays weather into deeply fissured, puffed-up slope deposits, the common appearance of pockets and irregular streamerlike clay masses in the surrounding sandstones and pellet conglomerates, are difficult to explain if the clays are ordinary fine stream or lake deposits. Recently, Waters and Granger (1953) have reported volcanic debris from Chinle shales, and point out that much of the finer material may be volcanic ash. Tests of purple Chinle clay by Willard show a high amount of montmorillonite, and bear out the assumption by Waters and Granger of volcanic admixtures in the clays.

The Chinle formation was named by Gregory (1917, pp 42, 43) from exposures in Chinle Valley, Arizona, about 30 miles northwest of the mapped area. He distinguished four units—A, B, C, and D—as follows:

> Division A: the highest strata: Red, brown, pink, or rarely gray calcareous shales and shaly sandstones, with a few thin beds of limestone and limestone conglomerate; form banded walls at the base of the overlying massive Wingate sandstone; intricately carved into buttes or distributed as a patchy floor over the topmost limestone stratum of division B. Type localities, Mesa de Ventana and Todilto Park.
>
> Division B: Gray, pink, and purple cherty limestone and light to dark red shale, in alternate bands. Limestone is massive or conglomeratic, in beds 1 to 6 feet thick, is highly resistant, and forms the caps of mesas and local plateaus; shales are thin, calcareous, mottled, and friable. Type localities, Carson Mesa, Leroux Wash.
>
> Division C: Shales and 'marls', with rare calcareous sandstone, all lenticular, exceedingly friable, variegated with tones of pink, red, ash, and purple; limestone conglomerate in lenses, short beds, and irregular masses is characteristic; gypsum is common, and petrified wood almost universal; weathers into mounds, buttes, and immature mesas with typical badland expression. Type localities: Cottonwood Wash, Black Creek Valley, and Beautiful Valley and Round Rock fossil forest.
>
> Division D: Dark-red, light-red, chocolate-colored, or rarely gray shales (70 per cent) and shaly sandstones (30 per cent) ; ripple marked, imbricated; brown conglomerate of lime and clay pebbles occurs in lenses; gypsum common; petrified wood in small amounts; bone fragments abundant; weathers into buttes and mesas divided by sharply cut miniature canyons, producing very rough topography. Rests unconformably (?) on the Shinarump conglomerate. Type locality, Chinle.

Later, Callahan (1951) considered that essentially all of the "A" member belongs to the Glen Canyon group (Wingate sandstone and Carmel member in this area). A widespread disconformity is generally recognized to be present near the contact of the original "A" and **"B"** horizons, at the base of a limestone-pebble conglomerate. Within the mapped area, Division B is about 350 feet thick, Division C about 600 feet, and Division D is relatively thin (Gregory, 1917, p 45), probably not over 250 feet.

Both the fossil plants and clams are believed to be of late Triassic age (McKee, 1951-a, p 91).

LOWER JURASSIC SERIES

GLEN CANYON GROUP

Wingate Sandstone

The Wingate sandstone crops out intermittently beneath the cliffs of Entrada and Carmel which form the eastern wall of Black Creek Valley and the surrounding walls of Todilto Park.

In the area of this report, according to Callahan (1951) and Harshbarger et al. (1951), a granule-pebble conglomerate may be taken as the base of the Wingate sandstone. The basal contact is well exposed only at the northern branch of Bowl Springs Wash, in northeastern Todilto Park. The top contact, although exposed at the northwest corner of Todilto Park, is difficult to draw, since the upper beds of the Wingate pass without lithologic break into the lowermost Carmel sandstone beds.

The Wingate in the area has a total thickness of about 265 feet; the lower part is about 135 feet thick, the upper 130 feet.

In most places, only the middle part of the Wingate sandstone forms a ledge, about 20 feet high, strongly crossbedded, feldspathic, and of brick-red color. Crossbedding is conspicuous also in the immediately underlying beds, but the lowest and highest zones are finer grained, more argillaceous and, where exposed, fail to show cross-bedding. These beds disintegrate easily, and the thick alluvium of the region commonly conceals the entire Wingate formation.

Apparently, the change from parallel-bedded to crossbedded sandstone reflects a change in the mode of deposition of fine sands in the region at the end of Chinle time. Whereas the parallel-bedded lower portion may be a fluviatile or lacustrine deposit, the crossbedded middle part is more probably a windblown deposit, perhaps including some reworked late Chinle sands. The rock is unfossiliferous; little else can be said about its origin.

The term "Wingate sandstone" was applied originally by Dutton (1885) to rocks composing the vertical red cliffs north of Fort Wingate, New Mexico. After an extensive study of the Jurassic rocks of the Colorado Plateau, Baker, Dane, and Reeside (1936) subdivided the cliff rocks into Entrada (upper) and Carmel (lower), and restricted the term Wingate sandstone to two units, the rocks beneath the vertical cliffs which commonly make a secondary line of low cliffs, and the rocks formerly defined by Gregory (1917, p 42) as the lower part of the "A" member of the Chinle formation. Both units are present in the area, but it was not practical to separate them in mapping. The Kayenta formation, which overlies the Wingate in the western part of the Navajo country; and the Navajo sandstone, which has its main development far to the northwest, are both absent in the area mapped, so that here the Wingate sandstone is overlain directly by the Carmel.

The Wingate sandstone, like all other Jurassic formations in this area, is unfossiliferous, and does not provide independent evidence of the Jurassic age of this group of sandstones. The assignment to the Jurassic system is based entirely on the correlation with other, similar sequences of strata that do show interbedded or intertonguing relations with fossiliferous rocks, in Utah, Colorado, and other districts of the Colorado Plateau.

SAN RAFAEL GROUP

To this group belong the succeeding four units: in ascending order, the Carmel, Entrada, Todilto, and Summerville. The naming of the formations, and their assignment to larger groups, was proposed by geologists of the U.S. Geological Survey, following detailed field work in south-central Utah (Gilluly and Reeside, 1928; Baker, Dane, and Reeside, 1936). With minor modifications, the nomenclature of the Utah sections is applicable in the Navajo country in northeastern Arizona and northwestern New Mexico (Harshbarger, Repenning, and Jackson, 1951, pp 95-99). However, the Carmel formation of Utah is relatively thin in the area mapped, and the manner of weathering is such that it cannot be mapped separately in the vicinity of Fort Defiance. Instead, it is included with the succeeding Entrada sandstone as a distinctive zone or member thereof.

Entrada Sandstone, Including "Cannel Zone"

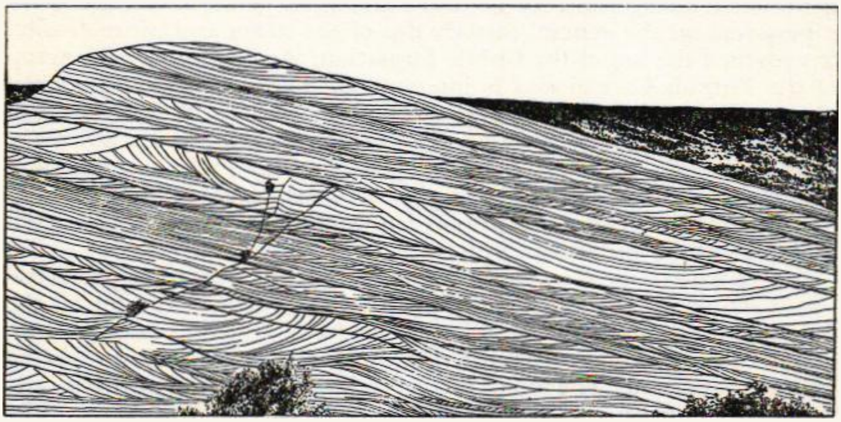
A vertical wall of brick-red color, strikingly crossbedded, and unique in scenic appearance, terminates the lowland of Black Creek Valley on the east (pl 2, Frontispiece). This is the Entrada-Carmel sandstone, which can be traced from the southeastern corner of Fort Defiance quadrangle northward to the west base of Zilditloi Mountain, and on to the northwest corner of Todilto Park, where it forms prominent, north-facing cliffs. At Todilto Park, a few gentle undulations are superposed on the general easterly dip of the strata and, since erosion has reached the top of the Chinle formation, the continuity of outcrop of the Entrada-Carmel cliff is interrupted. The depressed (synclinal) areas preserve the cliff-forming sandstones, whereas they have been eroded from the uparched areas. The brilliantly colored vertical walls, with pale-green meadows between, give Todilto Park its distinctive scenic quality and character. At the northeast end of Todilto Park, the sandstone cliff passes northward toward the settlement of Crystal and the vicinity of Sonsela Buttes.

The base of the Cannel is rarely exposed, but appears to pass without sharp boundary into the argillaceous, thin beds at the top of the Wingate sandstone. The top of the Cannel is a white sandstone bed, about 1 foot thick, that separates sharply the Carmel from the overlying Entrada sandstone. The top of the Entrada is drawn where the typically brick-red, massive-weathering sandstone is overlain by gray, thin-bedded, and lithologically different sandstones at the base of the Summerville formation, unless the Todilto limestone intervenes, as in northern and eastern Todilto Park.

The Cannel has a thickness of 50-80 feet, and that of the Entrada varies between 150 and 200 feet.

Its position at the base of the great Entrada cliffs, and the peculiar mode of weathering, distinguish the Cannel from all other Jurassic sandstones. The rock is very similar in composition to the Entrada, and the only difference is a slightly larger percentage of very fine sand (see pl 14, col E). Crossbedding is on a smaller scale than in the Entrada, the amount of feldspar is essentially the same in both rocks, and the brick-red color of the Carmel zone is very slightly darker than that of the Entrada. Yet, in all exposures, the Carmel zone is penetrated by hundreds of cracks, nearly vertical (but, in detail, crooked and irregular), producing knobs and a small-scale fluting and miniature relief not seen in other formations, and contrasting with the monotonous, smooth walls above (pl 2, Frontispiece). The reason for these innumerable cracks and the characteristic mode of weathering is not clear.

The Carmel zone comes to a sharp end at the white 1-foot sandstone layer at the top, and above it there rises usually a vertical wall, as much as 200 feet high, exhibiting huge exfoliation shells. This is the Entrada sandstone. Its pale brick-red color and massive weathering are characteristic in the entire Colorado Plateau. Impressive is the large-scale trough cross-stratification (McKee and Weir, 1953) not found on a similar scale in other formations. The structure differs from that of the De Chelly sandstone in showing well-developed festoons, or troughs (fig 10), strikingly resembling those of the Carboniferous Fountain and Casper formations of Wyoming (Knight, 1929, pp 56-72). There is abundant evidence that some of the red iron oxide has been leached from the Entrada. Gray lenses, spots, and narrow zones along joints and occult cracks mark areas where circulating solutions have removed the pigment, and in many cliffs and specimens one can see that the sand grains have been enlarged and terminated by crystal faces. Similarly,



CLIFF OF ENTRADA SANDSTONE SHOWING LARGE-SCALE CROSS-STRATIFICATION.

View northwest towards The Haystacks, due east of Fort Defiance.

Figure 10

many gray spots in the sandstone are seen under the microscope to be patches of chalcedony, in spherical masses of radiating fibers. The space between these spherules is occupied by rather large calcite anhedra, and carbonate enclosing mud particles is the prevailing cement of the rock.

South of Clay Springs Wash, and from there to the southern border of the area, the Carmel, Entrada, and overlying sandstone formations are close to an old erosion surface, and have been more thoroughly leached than elsewhere. A few hundred feet south of the quadrangle border, the formations are little more than heaps of loose, gray sand. Unfortunately, the local relief is so limited that it is impossible to know to what depth this leached condition extends. This is a matter of some importance, for it may decide whether such sand may be suitable as glass sand.

In central Utah, the Carmel formation passes into marine limestones with Upper Jurassic fossils (Gilluly and Reeside, 1928, pp 74, 75). The Entrada sandstone has not furnished fossils, but is known to underlie Upper Jurassic beds in Utah (the Curtis formation; see Gilluly and Reeside, 1928, p 79), and is, therefore, also of Upper Jurassic age.

As in previous examples, the survey of a limited area can hardly be expected to contribute new interpretations of the mode of origin of these crossbedded unfossiliferous formations. The relatively even-bedded type of stratification in the Carmel zone and the high amount of silty sand agree well with the assumption that much of the Carmel sandstone is the deposit of a large basin, communicating in central Utah with a marine area of deposition (Harshbarger, Repenning, and Jackson, 1951, p 97; Gilluly and Reeside, 1928, p 74). In part, therefore, the Carmel beds may be lacustrine deposits. In contrast, the crossbeds and festoons of the Entrada are, in all probability, windblown sand, but the interbedded parallel-stratified layers (fig 10) could be regarded as water-laid sand, deposited during intermittent floods.

The type locality of the Carmel formation is Mount Carmel, in the western part of Kane County, Utah, where it was first described by Gilluly and Reeside (1926). In New Mexico and eastern Arizona, the formation was split off by Baker, Dane, and Reeside (1947, p 1666) from Dutton's type "Wingate sandstone," and the upper part of Gregory's Chinle formation, division A (Gregory, 1917, p 48). Its appearance in the area as the lower part of the vertical red cliffs is similar to that at the type locality at Fort Wingate.

The type locality of the Entrada sandstone is Entrada Point, in the northern part of the San Rafael Swell, Utah, described by Gilluly and Reeside (1926). In eastern Arizona and New Mexico, it forms the upper part of Dutton's type "Wingate sandstone." Baker, Dane, and Reeside (1947) restricted the latter term to a lower unit and applied the name Entrada sandstone to the main, massive cliff-maker. The correlation of these and other Jurassic formations is summarized by Harshbarger, Repenning, and Jackson (1951, pp 95-99).

Todilto Limestone

The Todilto limestone crops out along the east and north sides of Todilto Park only. It is absent as a limestone along the west and south sides, and has not been found on the east side of Black Creek Valley.

The contact between the limestone and the underlying Entrada sandstone is generally gradational through an interval of silt and varicolored shale, but there is little evidence of channeling or disconformity.

The thickness of the limestone in the area varies downward from a maximum of about 14 feet, just north of Todilto Wash. Within a distance of about 4 miles toward the southwest, it is replaced entirely by an interval of limy sandstone, varicolored siltstone, and red shale. Measured sections at several points give an idea of the prevailing lithologies.

1. *A quarter of a mile north of Bowl Springs Wash. Dip 30° E.*

	Ft	*in.*
Seven 2- to 8-in. beds of limestone, separated by quarter-inch layers of reddish silt, grading downward from dense pure limestone into crosslaminated sandy limestone in thinner beds toward the base	3	
White, friable, medium- to fine-grained sandy siltstone	2	6
Medium-bedded (1-6 in.) dense crystalline limestone; fine laminae on weathered surfaces	1	10
Alternating layers, one-fourth to 1 in. thick, of dense aphanitic gray limestone and sandy fine-grained limestone or limy quartz-sandstone	2	3
Massive, fine-grained gray crystalline limestone; patchy areas coarsely crystalline; abundant calcite veins with slickensides	4	8
	14	3

2. *One and one-quarter miles southwest of Squirrel Springs Wash. Dip 7° SE.*

	Ft	*in.*
Dense gray limestone		6
Grayish-yellow flaggy sandstone	3	
Pinkish thin-bedded siltstone	3	
Lenticular bed of gray nodular limy sandstone, containing some small well-rounded black chert pebbles	4	
	10	6
Red silty shale		

3. One mile southeast of Beelzebub. Attitude N. 50° W., 8° S.

	Ft	*in.*
Orange-pink, thin-bedded, fine-grained sandstone . . .	4	
Pinkish, poorly cemented, thin-bedded to shaly siltstone	3	
Grayish-yellow, thin-bedded, irregular-weathering, nodular limy siltstone	2	
	9	—
Red massive siltstone		

An analysis by H. B. Wiik (Helsinki) of a sample from one of the massive purer limestone beds gave the following:

SiO_2	6.55%
$A1_20_3$	0.32%
Fe_2O_3 (total iron)	0.28%
CaO	51.90%
MgO	0.68%

As the foregoing sections show, the Todilto limestone in the mapped area is not wholly a limestone, but lenses in and out with fine sandstone and siltstone. This is to be expected near the boundary of the area of limestone deposition. Where present, the limestone may cap the cliffs of Entrada sandstone and cover most of the backslope of the cuestas, where the dip is sufficient to have produced subsequent valleys along the contact between the Entrada-Todilto and the overlying Summerville formation; or it may only form a notch or narrow bench in the cliffs, where the rocks are nearly horizontal. The limestone breaks down into slabs and blocks commonly found at the foot of the vertical Entrada cliffs.

Fossils have not been found in the Todilto limestone of this area. Farther east, in northwestern New Mexico, the limestone contains gypsum lenses, and it has been suggested that here was possibly a marine or brackish-water area, comparable with the marine basin of central Utah in which the Curtis formation was deposited (Smith, C. T., 1951, p 100), and that the two depressed areas were separated by a low arch, a predecessor of the Defiance uplift.

The name Todilto limestone was introduced by Gregory (1916, p 55) in reference to the exposures on the east side of Todilto Park. Baker, Dane, and Reeside (1936) originally believed it to be the basal member of the Morrison formation, but later work (Baker, Dane, and Reeside, 1947; Harshbarger et al., 1951) has shown it to be a part of the San Rafael group.

Summerville Formation

From the southeastern corner of Fort Defiance quadrangle, the Summerville formation extends northward on the east side of Black Creek Valley along the same line of cliffs as the Carmel-Entrada sandstone. It skirts the southwest and northwest base of Zilditloi Mountain and, as does the Entrada, passes from Todilto Park northward toward the Sonsela Buttes area.

Contacts with the underlying Todilto limestone are generally poorly exposed, but where the Summerville formation overlies the Entrada sandstone, the contact usually can be traced within some 2 to 3 feet. The top of the Summerville is more difficult to establish, and many geologists consider it unwise to draw a boundary here, and include the next higher sandstone member, the Cow Springs sandstone (Harshbarger, Repenning, and Jackson, 1951, p 97) in a more comprehensive unit. However, in the area of this report, the top of the Summerville formation has been drawn at the top of a prominent gray sandstone bed with polygonal cracks that were found in all outcrops (pl 7-A).

In a measured section south of Zilditloi Canyon, the Summerville formation has a thickness of 367 feet; on the east side of Todilto Park, it is 340 feet; in an incomplete section, 1½ miles north of the mouth of Twin Buttes Wash, 284 feet were measured.

The Summerville formation, in the restricted sense here adopted, forms a series of bold cliffs on top of the vertical Entrada cliffs. The outcrops are easily identified, since they are forested and recessed by several flat benches. In contrast to the Entrada sandstone, the Summerville formation consists of a dominantly parallel-stratified sequence of gray and pale brick-red or pinkish, fine-grained, moderately feldspathic sandstones. At intervals of 25 to 35 feet, more resistant sandstone is interbedded with darker brick-red shaly sandstones or siltstone zones, which cause the characteristic recesses in the cliff profiles of this formation. To what extent the gray color of so many sandstone layers is due to original absence of iron oxide, or due to removal of a primary iron oxide, has not been established. Near the top of the formation, a zone of massive-weathering, crossbedded, pale-pink to creamy sandstone crops out in barren flats, supporting at best a sparse growth of stunted piñon. The magnificently exposed top surfaces of this zone are crisscrossed by innumerable polygonal cracks that give it such a characteristic texture that the zone is identified without difficulty in the entire area (pl 7-A). Over most of the Black Creek Valley-Todilto Park district only one polygonal layer is developed, but south of Zilditloi Mountain two such layers appear, separated by some 65 feet of silty sandstone that lacks the polygons. Likewise, 2 miles south of Zilditloi Mountain, the basal beds of the next higher formation rest on the highest polygon sandstone, whereas elsewhere a poorly exposed zone of relatively argillaceous beds separates the gritty base of the Recapture formation from sandstone with polygons.

Under the microscope, the Summerville sandstone is an aggregate of quartz grains, 0.1 to 0.5 mm across, showing generally good rounding, and a cement of iron oxides, a little mud, and calcite. Even megascopically, the large size of some of the calcite crystals in the cement is noticeable. In the walls of the canyon south of Zilditloi Mountain poikiloblastic calcites are nodules, as much as 1 inch in maximum diameter. Much leaching and regrowth have affected the quartz grains. Enlarged euhedral crystals, projecting into minute cavities, or bounded by calcite cement, are common nearly everywhere. At the contact points, some quartz grains have apparently been partly dissolved and subsequently recrystallized, so that minutely indented contacts result. Likewise, at contacts with feldspar grains, silica has been dissolved, and the feldspars project into concave quartz grains. Neither at indented quartz grain contacts nor at feldspar projections into quartz is any iron oxide present. Close to the old land surface mentioned before, the calcite cement of the Summerville formation has largely been dissolved, as has also the iron oxide. This leaves a pale-gray to white, loose sand.

The dominantly parallel-stratified sandstone sequence of the Summerville formation is presumably a flood-plain deposit. The uniformly fine grain suggests that the area of deposition was far from the original source of the detritus. But whether the Summerville basin covered most of the previously deposited Todilto limestone, or expanded farther to the southwest or other directions, is not clear at the present time.

The sandstone formation above the Todilto limestone was originally believed by Gregory (1916) to represent the Navajo sandstone. Work by Baker, Dane, and Reeside (1947) has shown that it is correlative with the Summerville formation of the San Rafael Swell of Utah (Gilluly and Reeside, 1928, p 80), and is the uppermost unit of the San Rafael group, unconformably underlying the Morrison formation. The Summerville has recently been referred to as the Red Mesa formation by Hoover (1950), who believes that the above correlation is not valid. Perhaps for this reason the name Summerville in this area should be followed by a query (?).

MORRISON FORMATION

The prominent cliffs of the Entrada-Summerville sequence, that accompany the eastern slopes of Black Creek Valley from the southern border of the mapped area to Zilditloi Mountain, are separated from the pale-brown or gray cliff of the Dakota (?) sandstone by a long, rather featureless slope, dotted with piñon, and with few and irregularly distributed cliffs interrupting the monotony. This slope is underlain by the Morrison formation, and from Zilditloi Mountain, which surmounts the large, meridionally trending series of cuestas, the Morrison beds veer to the east, and then again to the north, fringing the brick-red cliffs and plateaus of Todilto Park like a broad frame.

Two subdivisions of the Morrison formation have been mapped: the lower Recapture shale member, and the upper Westwater Canyon sandstone member. Other subdivisions of the Morrison formation, proposed in various areas of the Colorado Plateau, have been considered, but in order to avoid mapping of very thin and discontinuous members, only the aforementioned two subdivisions appear on the map, and deviations and variations in lithology will be mentioned below.

The Recapture shale member includes an appreciable amount of poorly cemented sand, and the Westwater Canyon sandstone member contains argillaceous zones, especially near the top. The placing of the contacts is recognized, therefore, to be somewhat arbitrary, and in other areas other contacts may be preferable. The lower contact of the Recapture shale member was placed at the top of the Summerville formation, where rather coarse, locally gritty, poorly sorted and poorly cemented sands introduce a type of sediment not seen in the Summerville *sequence.* In places an erosional break is suggested, for instance on the north bank of a westward draining canyon at the north base of Zilditloi Mountain. Elsewhere the silty top beds of the Summerville formation pass without visible break into distinctly coarser sandstone beds, distinguished from the underlying Summerville by a pale-pink or creamy color. The top of the Recapture shale member has been drawn at the top of the highest shale zone, below the cliff-forming arenaceous Westwater Canyon sandstone sequence. The top of the Westwater Canyon sandstone member can be placed in most sections within a very few feet, for the Dakota (?) group introduces sandstones with contrasting weathering characteristics, or starts with dark-gray shales, locally with coal-bearing seams, not found in the Morrison beds.

Thicknesses for the Morrison formation are as follows:

Recapture shale member:

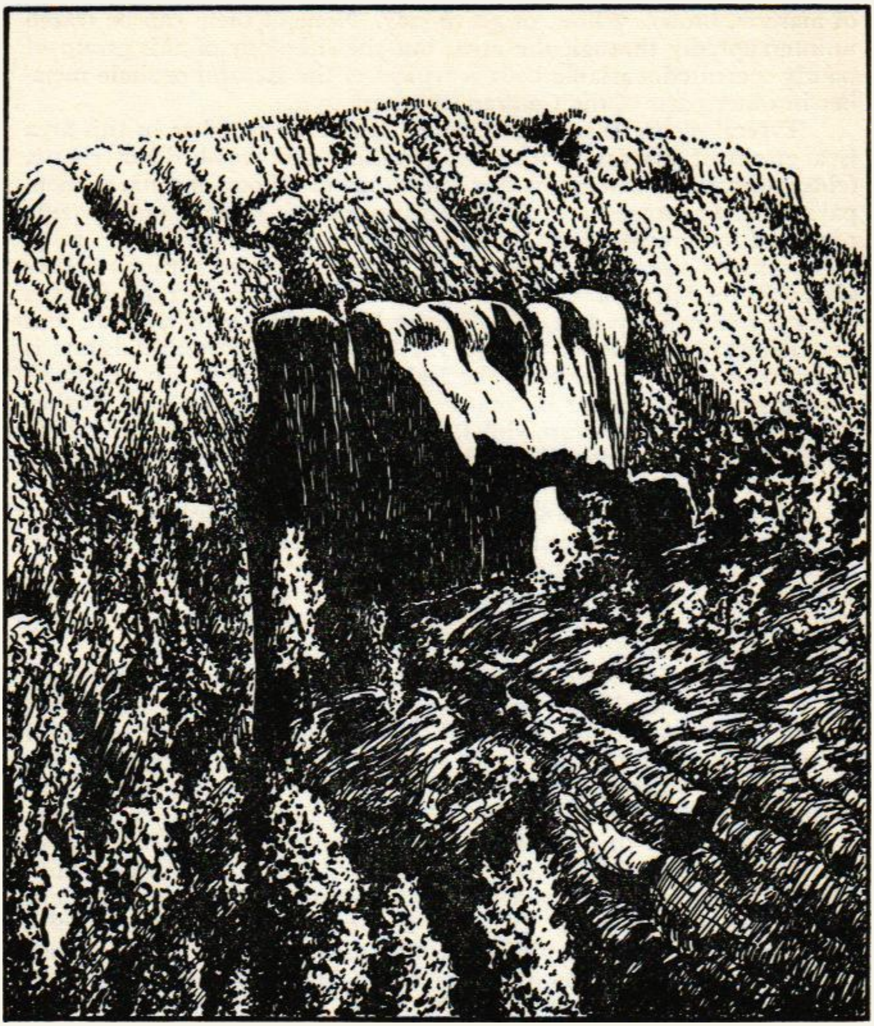
331 feet (south slope of Zilditloi Mountain) 521 feet (south side of Twin Buttes Wash) 330 feet (east side of Todilto Park)
552 feet (1 mile north of Twin Buttes Wash)

Westwater Canyon sandstone member:

257 feet (south slope of Zilditloi Mountain) 217 feet (south side of Twin Buttes Wash) 251 feet (east side of Todilto Park)
258 feet (1 mile north of Twin Buttes Wash)

Total thicknesses of the Morrison formation in the area: 591 feet, 810 feet, 738 feet, 314 feet (Westwater Canyon and incomplete Recapture).

The lower arenaceous beds of the Recapture shale member (possibly a tongue of the Cow Springs sandstone of Harshbarger et al., 1951) are pinkish or pale creamy-white, soft, parallel- or cross-stratified, fine-grained sandstones that weather into smooth, uniform slopes with little subdivision into benches and cliffs. The cement is largely calcareous but, as is so common in this region, it is partly dissolved, leaving a rather incoherent gray or pink sand. On the north and south side of Zilditloi Mountain, grit lenses of pale brown or russet color are striking intercalations in this series, for they give rise to peculiar, massive-weathering, steep-walled promontories (fig 11). The topmost 10 feet commonly are better cemented and, in weathering, produce unique bulbous formations. In the southernmost portion of its outcrop belt, near Clay Springs Wash, the Recapture shale member is either unusually thin, or its lower beds are concealed by alluvium. The pinkish basal sandstones are nowhere in sight, and the exposures begin at the base with white and greenish sand, with intercalated brown day lenses. Conceivably, a normal fault of north-southerly strike has cut out part of the formation, but the evidence is inconclusive, and the narrow belt of outcrop may as well be due to local lensing-out of the sandstone portion. The upper part of the Recapture shale member is easily recognized in the region by the prominent, barren surfaces of



CLIFF OF LOWER MORRISON GRITTY SANDSTONE RESTING ON SUMMERVILLE SANDSTONE (AT BOTTOM OF CANYON).

In distance north slope of Zilditloi Mountain, composed of talus-strewn upper Morrison shale and sandstone, capped by trachybasalt. Small white area near left margin of picture, and at level of natural bridge, is lapilli tuff pipe.

Figure 11

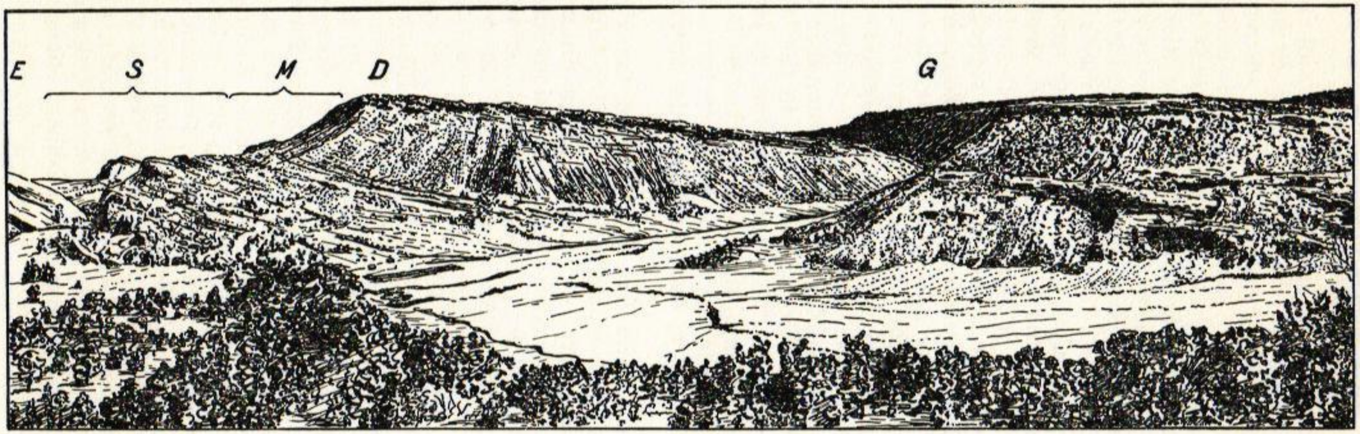
white to light-gray, or greenish, sand, interbedded with many lenses of maroon, brown, yellow, or green clay. None of them can be traced uninterruptedly through the area, but the lithology of this group of poorly cemented, variable beds is typical of the Recapture shale member in other parts of the Colorado Plateau.

Typical of the Westwater Canyon sandstone member in this area is a group of massive-weathering, parallel- and crossbedded, coarse, feldspathic, locally conglomeratic sandstones or arkoses of pink, salmon, pale-brick, or orange color. Noteworthy are single pebbles of quartzite, pink and red granite, chert, basaltic igneous rocks, and rhyolites ranging from pea size to 6 inches across. They are found through a considerable thickness of sandstone and make this member by far the coarsest sedimentary unit between the Shinarump conglomerate and the Dakota (?) sandstone. In fact, the Westwater Canyon sandstone is in many sections coarser than the Dakota (?) sandstones. In nearly all exposures, the sequence of coarse beds includes lenses and smaller pockets of chocolate-brown, violet, green, or yellow clay, some of which show concentric, contrastingly colored shells surrounding the core, usually of brown color. Finer-grained sandstone is common at the base of the orange, gritty arkoses, and calcareous cement seems to be the rule. It has been dissolved in places and causes the cliffs to weather with irregular surfaces, showing cavities, reentrants, and overhanging surfaces. Brown liesegang rings of iron oxides color many faces, and their sweeping curves, ignoring the orientation of the flat-lying bedding planes, simulate folds.

The coarse arkosic sandstone of the Westwater Canyon sandstone member is a lenticular deposit. The manner in which this material is inserted between the finer sand and shale lenses of the upper Morrison formation is well illustrated in the canyon walls surrounding the lower part of Twin Buttes Canyon. North of it, the orange cliff, rarely more than 120 feet thick, reaches up to the base of the Dakota (?) sandstone, and is exposed in this position for several miles north. However, in the north wall of the canyon, the sandstone dwindles down to thin, isolated lenses, and their position is somewhat below that of the main cliff farther north (fig 12). In a west-facing scarp, at the entrance of a tributary 1 mile east, the pink sandstone thickens as a strong cliff, but remains 70-100 feet below the base of the Dakota (?), and from here southwestward one can see how the coarse sandstone gradually rises in the section until, at the southwest promontory of the main canyon wall, it has resumed its normal position below the Dakota (?). Four and a half miles south, north and south of Clay Springs Wash, the Westwater Canyon sandstone increases in thickness from about 135 feet, north of the canyon, to about 270 feet, south of it. Here the arkose is either in direct contact with the Dakota (?) sandstone, or has no more than 26 feet of argillaceous beds at the top.

The uppermost member of the Morrison formation in the Navajo country commonly has been referred to as the Brushy Basin shale member. Though the topmost beds of the Westwater Canyon sandstone sequence become fine-grained, and locally pass into maroon sandy shale, it has not been considered desirable to separate this thin

Figure 12



VARIATIONS IN UPPER MORRISON STRATA ON NORTH SIDE OF TWIN BUTTES WASH.

East-dipping beds, from west to east, are: E, Entrada sandstone; S, Summerville formation; M, Morrison formation; D, Dakota (?) sandstone; G, Gallup sandstone. Mancos shale is not shown. In the large cliff, to left of center, the Dakota (?) sandstone overlies thin pink sandstone lenses and varicolored silty shale of the upper Morrison formation, resting on dominantly white sands and brown shale of Recapture shale member. In bluff on right, a resistant sandstone (Westwater Canyon member) appears, about 100 feet below the base of the Dakota (?). At position of observer, the Westwater Canyon member underlies Dakota (?) sandstone as cliffs 150 feet high.

group of beds, rarely more than 10 feet thick, and dearly distinguishable in a few places only.

The conditions of deposition of the Morrison formation *have* been discussed by many authors, and in the northern and central Rocky Mountains, where the famous dinosaurs have been discovered, the evidence for a fairly moist, locally swampy lowland is believed convincing. However, the character of the Morrison beds in New Mexico and northeastern Arizona favors the belief that the relatively sandy, and commonly crossbedded sediment was deposited in a more arid climate, and that the relatively sterile environment, in which the earlier Jurassic sandstones were deposited, continued without major interruptions till the end of Morrison time. The various clay lenses in the Recapture member may signify the filling of scattered, small depressions with finest detritus washed or blown together in these featureless plains. The fine-grained silty sandstones may in part represent windblown sand. But the thick accumulation of coarse arkose, sharp sand, and large pebbles in the Westwater Canyon sandstone is a new litho-logic element in the Morrison sedimentation. It suggests that a variety of older rocks became exposed to erosion, and that considerable volumes of detritus were accumulated rather swiftly, so that sorting was poor, and thousands of single pebbles remained scattered in this grit. Work on the nature of the rocks found aspebbles in the Westwater Canyon member has not yet been completed, but promises interesting information on the kinds of material that were attacked by late Morrison erosion. Whether some of the clay in the Morrison formation is of dominantly volcanic derivation, as some Chinle shales appear to be, is not yet certain.

The Morrison formation was first described in the vicinity of Denver, Colorado (Emmons, Cross, and Eldridge, 1896; Cross, 1894), and has been traced over large parts of the Rocky Mountains and Great Plains, but the correlation of its constituent subdivisions has proved difficult, because thickness, lithology, color, and fossil content vary greatly from one area to another. Many problems of the correlation in the Colorado Plateau area have recently been discussed by Smith (1951, pp 99-102). A good synopsis for the region of this report has been given by Harshbarger, Repenning, and Jackson (1951, pp 97-98). The terms Recapture shale member, and Westwater Canyon sandstone member, were introduced by Gregory (1938, pp 58, 59), and their adoption in this report should be regarded as tentative, though following present usage by geologists of the U.S. Geological Survey. The lithologic sequences in the Morrison formation in the area mapped do not, in our opinion, necessitate adoption of the rather inclusive term Cow Springs sandstone (Harshbarger, Repenning, and Jackson, 1951, p 97). The name Bluff sandstone member (Baker, Dane, and Reeside, 1936, p 21), for the lowest part of the Morrison formation, may be better than Recapture shale member; however, in view of the appreciable amount of admixed shale and clay in this member, the latter appears more nearly correct. It is recognized, moreover, that as correlation in this part of the Navajo Reservation advances, changes in the terminology may be necessary.

The Morrison formation is considered to be late Jurassic to early Cretaceous in age, and on the basis of the most probable age of the *Stegosauria* found in Wyoming and Montana, the formation is believed for the most part to be of late Jurassic age. The mapped area contains only unfossiliferous beds, and does not contribute any independent evidence as to the age of the formation.

UPPER CRETACEOUS SERIES

DAKOTA (?) SANDSTONE

The Dakota (?) sandstone forms the upper part of the highest cuesta along the eastern and southern edges of Todilto Park and continues south towards the center of the southern edge of the area, becoming progressively more dissected and less conspicuous southward.

The thin sandstones and carbonaceous shales of the lower part of the Dakota (?) sandstone lie disconformably upon the Westwater Canyon sandstone member of the Morrison formation. The upper massive sandstones form the cuesta ridge, and the highest thin sandstone members frequently form flatirons on the cuesta backslope or low ridges near the foot of the slope.

In three measured sections, the Dakota (?) sandstone ranges from 218 to 253 feet in thickness, with a sandstone to siltstone-and-shale ratio of about 1 to 1.5 (see pl 11).

Gregory (1917, p 72) has described the formation in general terms which leave little room for improvement:

> The Dakota sandstone is highly variable in structure, texture, and composition. It is characterized more by a persistent combination of features than by the persistence of any given bed. The base is commonly but by no means universally marked by conglomerate and the top is in many places a coarse brown or gray sandstone bed but may be a group of interbedded sandstones and shales or wholly sandy shale of yellow or gray tones. Coal lenses occur prevailingly in the middle of the Dakota but are found in all positions from top to bottom. The formation is *everywhere* lenticular; lenses and wedges of sandstone, of conglomerate, of shale, and of coal tens of feet or a few inches thick overlap, appear, and disappear along the strike and vertically in a most capricious manner.

The sandstone units range in thickness up to nearly 80 feet, but are commonly less than half that thick. The general order of succession consists of a lower siltstone, shale, and coal sequence up to 100 feet thick, one or two massive sandstones less than 80 feet thick, and an upper fine-grained sequence about 80 feet thick, with three thin sandstone beds. The sandstones are composed predominantly of homogeneously yellowish-gray (5Y7/2),* well-cemented, medium- to fine-grained, moderately well-sorted sandstone composed of equant, subrounded quartz grains with a rough surface texture in a clay matrix.

The sandstones occur as tabular and lenticular bodies which may lens out or thicken within a few hundred feet. The base of the individual beds is sharp and even for the lower members, and gradational in the upper members of the formation. Bedding within the units may

* Color symbol (Goddard et al, 1951).

be horizontal or cross-stratified; and ranges in thickness from less than 1 foot to over 10 feet, averaging from 2 to 6 feet. Jointing is common. Iron oxide concretions are found infrequently.

Outcrops occur commonly in vertical cliffs and exposures are good. The sandstones weather to a pale yellowish-gray (5Y8/2) and form a rubble which covers much of the shale sections below the cliffs.

The finer-grained units in the Dakota (?) sandstone range in thickness up to over 100 feet, but are commonly less than 80 feet thick. They are variable in grain size and color, ranging from gray to black and from very fine sandstone to siltstone to claystone.

Carbonaceous material is commonly admixed with clay, and at least three coal horizons ranging from less than 1 inch to 2 feet thick appear throughout the section. The shale units form regular rubble-covered slopes with poor exposures.

The Dakota (?) represents the sediments deposited under coastal-plain and near-shore conditions by the first recorded seaway to enter the area. The carbonaceous shales and coals were probably lagoonal deposits, the sandstones beaches and offshore bars.

The term "Dakota group" was first applied by Meek and Hayden (1862) to sandstones and clays of Upper Cretaceous age occurring in hills back of the town of Dakota, Nebraska. The term Dakota sandstone has been applied to rocks appearing in widely separated mid-continent localities, where in many cases (as in the Black Hills) they have been subsequently found to be of different age from that at the type locality. The U.S. Geological Survey prefers to use the name Dakota (?) sandstone for occurrences west of the Colorado Front Range.

No fossils were found in the Dakota (?) sandstone, except for unidentifiable plant fragments in the coal and carbonaceous shales. Pike (1947, pl 11) found a zone of *Gryphaea newberryi* 15 or 20 feet above the top of the sandstone. This is of Graneros age; hence the Dakota (?) in this area may be either Graneros or Dakotan in age.

MANGOS SHALE

The Mancos shale occupies a subsequent valley between the Dakota (?) and Gallup sandstone cuestas which varies from 500 feet in width near the north edge of the map to over 2,500 feet near the south edge, where the valley is drained by several streams flowing into Black Creek Valley to the west. The trend of the valley is north and south except for south of Todilto Park, where it swings eastward north of Twin Buttes.

East of Todilto Park, the valley bottom is deeply alluviated, and outcrops of shale occur only in a few places in the bottoms of the deep gullies which cut the Nakaibito alluvium. South of Todilto Park and west of the Manuelito Plateau, the slopes below the Gallup cuesta are mantled with landslide debris, and only a few gullies cut through and expose Mancos shale above the Dakota (?) sandstone.

At least one persistent sandstone ledge forms a prominent low ridge paralleling the eastern side of the valley; sandstone outcrops of this ledge are more abundant than shale outcrops. Although the shale extends well up the slope beneath the Gallup sandstone, it is mantled throughout most of the area by Gallup sandstone debris and talus. Its conformable lower contact has been mapped at the top of the uppermost of three thin sandstones included in the Dakota (?) sandstone.

The Mancos shale varies from 630 to 750 feet in thickness along the eastern side of Todilto Park. Farther south, dips were so low that an accurate estimate of thickness could not be made.

The Mancos shale also has been reported (Pike, 1947) to inter-tongue at two higher positions in the Mesaverde section, the Mulatto tongue at the base of the Dalton sandstone, and the Satan tongue within the Point Lookout sandstone. These will be mentioned in their stratigraphic order.

The main body of the Mancos shale, although poorly exposed, is predominantly a homogeneous, buff-weathering, grey- to black-colored, thinly laminated quartzose siltstone and silty shale. Subordinate lenses of sandstone up to 10 feet thick occur within the section, especially near the middle; some of these form long ridges within the valley. They are pale yellowish-orange (10YR8/6) to white- and grey-colored, laminated, medium-bedded, coarse- to fine-grained quartz sandstones with equant, subrounded grains in a clay or calcareous matrix. In places they are highly calcareous and fossiliferous. Generally they are well cemented.

The Mancos shale was named by Cross (1899) for exposures in Mancos Valley and about the town of Mancos, southwestern Colorado. Fossils collected by Pike (1947) in the area indicate that the shale here includes rocks of Graneros, Greenhorn, and Carlile age, but none of Niobrara age appears to be present.

The Mancos sea was never deep nor far from shore, as its predominantly silty character attests. Probably the shoreline was never more than a few tens of miles to the southwest.

MESAVERDE GROUP

Approximately one-third of the area mapped (over half of Tohatchi quadrangle) is underlain by rocks of the Mesaverde group. The western boundary with the underlying Mancos shale approximates the western edge of Tohatchi quadrangle, except where the contact swings east around the Todilto Park uplift. Chuska sandstone and landslide debris therefrom unconformably overlie the Mesaverde group in the northeastern quarter of the quadrangle; only two small outcrops of the Tohatchi formation appear in the extreme northeast corner of the area. Much of the surface of the Manuelito Plateau and Chuska Valley is covered with alluvium and soil, but in most of the remaining Mesaverde terrane badlands and fairly good exposures predominate.

The physiographic expression of the sandstone, siltstones, and shales which compose the Mesaverde strata depends partly upon their angle of dip. In the Manuelito Plateau, where they approach horizontality, exposures are poor except in the canyons, and the surface is gently undulating. At the east edge of the plateau, the beds steepen up to 15 degrees, with the development of cuesta ridges and subsequent valleys. Within this belt the Gallup, Dalton, Point Lookout and, to a lesser extent, sandstone units in the Menefee formation are the dominant ridge and cuesta-makers. Their relative resistance to erosion is indicated diagrammatically by the width of the columns in Plate 11 (in Pocket). Farther east, where the beds flatten out and massive sandstone horizons become scarce, typical badlands and low mesas, capped either by terrace gravels or by horizons of iron-cemented concretionary sandstone, have been developed.

The maximum thickness of the rocks of the Mesaverde group measured in the area is about 3,600 feet. The individual sandstone units and intermediate siltstone and shale units are lenticular and variable in thickness within the area. This variability is indicated diagrammatically in Plate 11 and Figure 13.

In spite of the widespread outcrops in the Mesaverde terrane, it is difficult to obtain reliable attitude readings, first, because of almost universal cross-stratification within the sandstone units, and second, because of the weathered and disintegrated nature of even the best exposures of the intervening shale and siltstone.

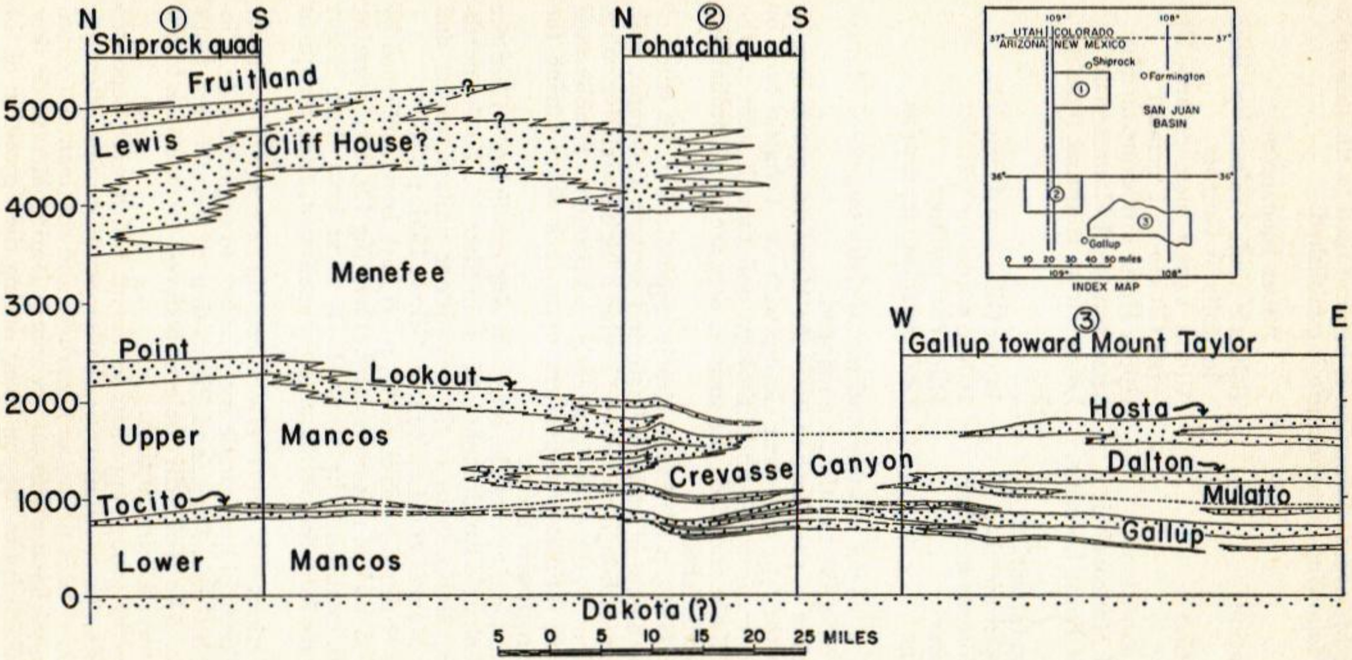
The formational units of the Mesaverde group are first described in relationship to each other and then individually.

The Mesaverde was described first by Holmes (1877) as a group containing three lithologic units, in exposures in the valley of Rio San Juan of western Colorado and northwestern New Mexico. Later (Cross and Spence, 1899) it was redefined in LaPlata quadrangle as a formation. Collier (1919) replaced Holmes' descriptive terms with geographic terms (Cliff House sandstone, Menefee formation, Point Lookout sandstone), and Sears (1925, 1934) and Hunt (1936) divided the Mesaverde formation on the southern edge of San Juan Basin into the following members (listed in approximate stratigraphic order):

NAME	PUBLICATION	ORIGIN OF NAME
Allison barren member	Sears (1925)	Allison (village)
~~Hosta sandstone member~~	~~Sears (1934)~~	~~Hosta Butte~~
Satan tongue of Mancos	Sears (1934)	Satan Pass
~~Gibson coal member~~	~~Sears (1925)~~	~~Gibson (village)~~
Bartlett barren member	Sears (1925)	Bartlett Mine
Dalton sandstone member	Sears (1934)	Dalton Pass
Mulatto tongue of Mancos	Hunt (1936)	Canyon Mulatto
Dilco coal member	Sears (1925)	Dilco (village)
Gallup sandstone member	Sears (1925)	Gallup (town)

This terminology for the Mesaverde was established on an arbitrary basis "for convenience in description," being distinguished by lithology and ~~"by the presence or absence of valuable coals" (Sears, 1925, p 16). It is not a~~ practical basis for division in the area mapped, although the lithologic equivalents of most of the above units are identifiable.

As a result of considerable discussion with members of the U.S. Geological Survey who are familiar with the Mesaverde rocks in San



COMPOSITE DIAGRAM SHOWING RELATIONSHIPS BETWEEN CRETACEOUS UNITS ALONG THE WEST AND SOUTH SIDES OF SAN JUAN BASIN.

Area between Shiprock and Tohatchi quadrangles largely hypothetical. (1) Beaumont (1953); (2) This bulletin; (3) Sears (1934).

Figure 13

Juan Basin, the Mesaverde formation is herein raised to the rank of a group, and the following nomenclature is established:

NEW USAGE	FORMER EQUIVALENCIES
Tohatchi formation	Tohatchi shale as described lithologically by Gregory
Menefee formation	Allison barren member and Upper Gibson coal member Upper
Point Lookout sandstone Satan tongue of Mancos shale	Hosta sandstone member Satan tongue of Mancos shale Lower
Hosta tongue of Point Lookout sandstone	Hosta sandstone member
Crevasse Canyon formation Lower	
Gibson member Dalton	Lower Gibson coal member
sandstone member Dilco	Dalton sandstone member
member	Dilco coal member
Gallup sandstone	Gallup sandstone member

The Bartlett barren member and the Mulatto tongue of Mancos shale were not recognized in the area mapped.

Although most of the above units of the Mesaverde group may be correlated from the type area near Gallup with the Tohatchi area by thickness, sequence, interval, and lithology, and though some of the units may actually be traced on the surface, they are in all probability not strict age equivalents.

As Spieker (1949, p 69) has so clearly emphasized in his study of Mesaverde equivalents in eastern Utah and western Colorado, such similar sequences, although apparently having a high correlative value, do not prove identity, since the apparently independent variables used in correlation are intimately dependent upon each other during the transgressive or regressive cycles.

A diagrammatic sketch of the intertonguing conditions within the Mesaverde in Tohatchi quadrangle is given in Plate 11. To the northeast, in San Juan Basin, many of these sandstone units disappear and are replaced by Mancos and Lewis shale (Silver, 1951, p 110).

The trends outlined by Pike (1947, p 31) have been confirmed by the more detailed work of this survey and others (fig 13), corroborating the picture first established by Sears (1941) of at least three major shoreline advances from the northeast to the southwest, and subsequent retreats.

Fossil collections by Pike (1947) indicate that the age of the lower Mesaverde in Tohatchi quadrangle is equivalent to upper Carlile, Niobrara, Telegraph Creek, Eagle, and Pierre time of the standard Colorado time scale. The Tohatchi shale is believed to extend into the Montana and lower Laramian time.

The Mesaverde group represents sediments which were deposited under three different environments: shallow-water marine, shoreline (including offshore bars, deltas, and beaches), and continental (coastal plain and lagoonal flood plains and swamps). During Mesaverde time the shoreline, which lay to the southwest during the deposition of the

Mancos shale, retreated across the area towards the northwest, then advanced partly across the area to deposit the Satan tongue, only to retreat again far to the northwest. The sandstone units of the Gallup, Dalton, Point Lookout, and lower Tohatchi are believed to represent beach and offshore bar deposits, the sandstones within the Menefee and Crevasse Canyon stream-channel sandbars. Shoreward from the beach and offshore bars the lagoonal coal swamps and carbonaceous flood-plain deposits were laid down; seaward the finer siltstones of the Mancos tongues were deposited. The major fluctuations of the shoreline may have been due either to eustatic movements of the sea (rise and fall of sea level), to orogenic movements of the hinterland to the southwest, or to periodic downwarping of the sea basin to the northeast. These movements caused increase or decrease in the supply of sediment to the rivers bringing in the sediments, or increase or decrease in the size of the sedimentary particles. Some of the thin sandstones undoubtedly represent seasonal floods; others may represent uplifts of the source area.

Gallup Sandstone

The Gallup sandstone, where it is crossed by Squirrel Springs Wash southeast of Todilto Park, consists of two massive well-exposed cliff-forming layers of yellow-gray sandstone, each nearly 80 feet thick, with an intervening 14-foot bed of gray carbonaceous shale and a 6-inch bed of coal. Basal contacts are sharp, even, and parallel.

Northward these massive sandstone units split and thin, with intercalation of thin units of medium-grained, angular, poorly-sorted sandstones, variegated red, gray, chocolate-brown, and black siltstone, silty shale and thin coal. The total section 2 miles from the north map edge measures only 97 feet thick. These units may form small vertical cliffs of irregular slopes; outcrops are less well developed than in more massive beds.

Southwards also the Gallup divides into three and, near the edge of the map, four sandstone units, the next to lowest being nearly 100 feet thick, the others ranging from 25 to 45 feet, with interbedded thin sandstones, siltstones, shales, and thin coals which bring the total thickness to nearly 300 feet.

In the Squirrel Springs Wash section (p1 11, sec 3) the upper sandstone is homogeneously colored; the lower is banded grayish-orange (10YR7/4?) on both fresh and weathered surfaces. Poorly sorted, coarse- to fine-sized quartz grains make up from 75 to 90 percent of the rock, with a clay matrix and small amount of feldspar and rock fragments. The sand grains are equant and subrounded, with rough surfaces. Cementation by clay and iron oxide is fair to good.

Crevasse Canyon Formation

The name Crevasse Canyon formation is applied herein to the sedimentary units which lie between the top of the Gallup sandstone and the base of the Point Lookout sandstone, and the type locality is established in the area of excellent exposures which lie on a north fork of Catron Creek about 3 miles southwest of the mouth of Crevasse Canyon (pl 11, secs 7, 8, 9).

The formation ranges from 420 to 620 feet in thickness in the northern sections measured, thickening to the south of Crevasse Canyon, as it replaces the rapidly thinning Point Lookout sandstone, to about 700 feet at the type section.

Its lower contact with the uppermost member of the Gallup sandstone is sharp and well defined, as evidenced in Section 1 (p1 11) on the north fork of Todilto Wash:

	Ft	*in.*
Thin-bedded fissile siltstone	25	
Coal		6
Shale and laminated siltstone	10	
Coal		8
Yellow to brown claystone		6
Coal	3	
Gallup sandstone		

Three members of the Crevasse Canyon formation may be differentiated in the area: the Dilco, the Dalton sandstone tongue, and the lower Gibson. The Mulatto tongue of Sears (1934) and Pike (1947) was not recognized in the area.

Dilco member. The Dilco member consists of 240 feet of silty shale, laminated siltstone, thin coal, and thin- to medium-bedded fine-grained sandstone, the latter being more abundant toward the top of the unit. The member thins toward the south and at Section 7 (pl 11) consists of 81 feet, as follows:

	Ft	*in.*
Dalton sandstone		
Medium- to thin-bedded fine-grained sandstone and siltstone in alternating layers	37	
Coal		6
Carbonaceous siltstone with thin sandstone layers and abundant gypsum	8	
Thin-bedded siltstone	10	
Friable fine-grained sandstone	10	
Carbonaceous siltstone with abundant gypsum crystals near top	1	
Friable fine-grained silty sandstone	15	
Gallup sandstone		

Colors are homogeneous in individual beds, but range from white through buff to pale olive-brown and gray and black. Texture ranges from coarse sand to fine clay, very fine sand and siltstone being most abundant. Sorting is poor, much of the laminated siltstone being half clay and half quartz, the latter consisting of equant, angular grains. Cementation is fair to good.

No evidence was found to justify a separation from the Dilco member of a Mulatto tongue of Mancos shale.

Dalton sandstone member. The Dalton sandstone member throughout most of the area is composed of two sandstone units from 20 to 45 feet thick, occupying an interval of from 40 to 72 feet. Toward the southern edge of the map the lower unit disappears and the upper unit thins markedly.

The base is usually gradational, as is illustrated in Section 1 (pl 11) exposed on the north fork of Todilto Wash:

	Ft	in.
Lower Dalton sandstone, cliff and smooth-slope exposure of orange-pink, massive, homogeneous thick-bedded, medium- to fine-grained quartzose sandstone	36	
Covered	3	
Crosslaminated silty sandstone	2	
Clayey siltstone, mostly covered	10	
Fissile to medium-bedded fine-grained sandstone	3	
Covered	6	
Fissile to medium-bedded crosslaminated sandstone	3	
Thin-bedded siltstone	3	
Medium-bedded to fissile sandstone	3	
Thin-bedded siltstone	5	
Thin-bedded siltstone	3	6
Covered		

The lower unit of the Dalton sandstone is a homogeneous orange-pink (5YR7/4) sandstone, with massive beds from 3 to 24 feet thick composed of coarse- to fine-grained, moderately well-sorted quartz grains in a clay matrix. Grains are equant and angular to subrounded. Cementation is variable.

The upper unit is characteristically pale-gray and white, but locally takes on a grayish-orange (10YR7/4) color, with massive and crosslaminated beds from 1 to 10 feet thick. It is composed largely of coarse- to medium-grained, well-sorted quartz and lesser amounts of feldspar and rock fragments in a clay matrix. Grains are equant and angular to rounded. Cementation is only fair.

Lower Gibson member. The lower Gibson member ranges from 135 to 345 feet in thickness in the northern part of the area, and thickens southward, as it replaces the Point Lookout sandstone, to about 550 feet on Catron Creek (pl 11, secs 8, 9). It is very poorly exposed in the north, good exposures appearing only south of Crevasse Canyon. At this point it consists of gray papery shale, carbonaceous shale and coal, shaly siltstone, thin-bedded sandy siltstone, and silty sandstone, with 5 to 10 units of massive, crosslaminated, medium-grained, pale grayish-yellow (5Y8/4), friable sandstone, usually with an iron-cemented concretionary capping a few feet thick, overlain commonly by several feet of extremely friable and poorly consolidated sandstone.

The base of the member is a sharp contact between carbonaceous silty shale and the underlying white Dalton sandstone.

Coal beds become more numerous and thicker as one progresses southward; the thicker beds occupy an interval of about 200 feet in the middle of the unit. Most of the coals of commercial thickness occur south of Catron Creek, only a few to the north. Correlation of coal beds suggests that the lower part of the section is thickening very rapidly in the Catron Creek area, or that the carbonaceous section is rising rapidly (see fig 3).

Point Lookout Sandstone

The Point Lookout sandstone southeast of Todilto Park (pl 11, sec 3) is made up of one thin and two thick units, totaling 320 feet. Northward the thick units are separated by a tongue of finer-grained material (the Satan tongue of Mancos shale), so that the combined thickness reaches nearly 400 feet; south of Crevasse Canyon within 1 mile they thin abruptly to 25 feet and completely disappear within 2 miles.

The lower cliff-making unit, here called the "Hosta sandstone tongue," is a homogeneous-colored, pale-orange to pale yellowish-gray (10YR8/2 to 5Y8/2), massive and faintly crossbedded, medium- to coarse-grained arkosic sandstone with clay matrix. Feldspar grains are subordinate to quartz, both being equant, angular to subangular, with rough surface texture. Jointing is poorly to well developed. Cementation is fair to good. Iron oxide concretions are uncommon. Below this unit is 12 to 42 feet of a poorly cemented, thin-bedded sandstone with an otherwise similar lithology.

Fossiliferous beds (shark teeth, pelecypods), which represent the "Satan tongue of Mancos shale" between the lower and upper cliff-makers, form an irregular slope consisting of up to 120 feet of homogeneously colored, buff to yellowish-orange, alternating beds of fissile to massive sandstones and intervening siltstone and shales. A representative 120-foot section (pl 11, sec 1) is as follows:

	Ft	*in.*
Point Lookout sandstone		
Fissile and thin-bedded silty sandstone	3	
Massive sandstone beds 4 to 5 feet thick	20	
Thin-bedded, friable, silty sandstone	4	
Silty shale	10	
Massive sandstone	1	
Silty shale	5	
Thin-bedded silty sandstone	1	
Massive crossbedded sandstone	5	
Thin-bedded sandstone	7	
Covered (silty shale?)	6	
Thin-bedded silty sandstone	4	
Crossbedded sandstone, worm tracks or borings	2	
Covered (silty shale?)	20	
Massive sandstone bed, ripple marks and worm tracks	15	
Thin-bedded silty sandstone	7	
Covered (silty shale?)	10	
Hosta sandstone tongue of Point Lookout sandstone		

The Point Lookout sandstone differs from the Hosta sandstone tongue in color; it is a darker shade of orange (10YR7/6) and has more abundant iron-oxide concretions. Otherwise its texture, grain size, and other characteristics are very similar.

In the northernmost section measured (pl 11, sec 1), only the lower 60 feet of the Point Lookout are well cemented, the upper part of the sandstone being poorly exposed, paler in color, and with little topographic expression. Included finer-grained beds tonguing in from the north are probably present, but no exposures were seen.

Menefee Formation

The rocks of the Menefee formation crop out east of Crevasse Canyon and Manuelito Plateau, and south of Chuska Mountain; they appear in a discontinuous narrow strip east of Todilto Park, and a few isolated outcrops show through the landslide cover southeast of Chuska Mountain. The badlands which cover large areas west and north of Mexican Springs and Tohatchi are cut largely in this formation.

North of Crevasse Canyon the sandstones, siltstones, shales and coals which make up the unit lie upon the Point Lookout sandstone; south of Crevasse Canyon the mapped contact is an arbitrary one, based upon discontinuous, thin sandstone lenses which were traced southward along the horizon occupied northward by the top of the Point Lookout.

The lower 500 feet of the unit contain carbonaceous shales and thin coals, and are the equivalent environmentally of the upper Gibson coal member of Sears (1984), whereas the rest of the section above is the equivalent of the Allison barren member of Sears (1925).

Two sections (pl 11, sea 5, 6) have been measured and described in detail (special report). The northern section (5) is complete to the base of the overlying Tohatchi formation, giving a thickness to the Menefee formation of 2,290 feet. The southern section (6) measured southeast from Crevasse Canyon, describes 1,400 feet of sediments lying above the Point Lookout sandstone. A third section along Catron Creek (pl 11, sec 9) extends 1,200 feet above the inferred contact. In the above three sections the ratio of sandstone to siltstone-and-shale ranges from about 1:4 in the north to more than 1:3 in the south.

The sandstone units are extremely variable in thickness (up to 50 feet) and discontinuous in extent. Where present they are cuestaformers, but they appear to occupy channels, and may pinch out within a few hundred feet. They are usually characterized by iron-oxide cementation, frequently forming in large pillow-shaped concretions (pl 8-B) which cap the sandstone units. In the lower 1,300 feet measured there are 13 such units, but correlation, even between sections only a few miles apart, is doubtful, without tracing each of them along the outcrop. A few of these units are indicated by dotted lines on Plate 1. The sandstone is generally grayish-orange (10YR7 /4), homogeneously colored, poorly cemented and friable, massive, medium- to fine-grained, and faintly crosslaminated. The iron-cemented cap rock is medium-brown (5YR5/4), frequently crosslaminated, and platy or rounded and botryoidal.

The intervals between the sandstones are occupied by yellowish-gray (5Y7/2) to light olive-gray (5Y5/2) and dusky-yellow (5Y6/4), fine-grained, silty, friable sandstone, sandy siltstone, silty clay with minor amounts of gray shale, carbonaceous shale, and generally impure coal. One thin lens of impure limestone (39 percent insoluble) was observed 780 feet above the base of the formation in Section 5. Petrified and carbonized wood, gypsum flakes and crystals, and sparse vertebrate reptilian bone fragments weather out of these rocks and are found as float.

Tohatchi Formation

The Tohatchi shale was described by Gregory (1917, p 80) from two areas of outcrop 2 miles north and 3 miles west of Tohatchi Indian School, as consisting of alternating beds of poorly consolidated clays and sands with a few strata of impure lignite:

> The stratification is very irregular; the shales and sandstones and carbonaceous layers are little more than lenses of moderate dimensions that overlap and interleave; few of them retain their individuality for distances greater than 200 feet. The sandstone beds are 10 to 30 feet thick and include lenses of drab and red-brown shale, irregular chunks of clay, balls of pyrite, and concretionary masses of manganese and iron displayed as irregular bands and flattened spheres. The sandstone layers are brown, yellow, gray, and white and are composed of well-rounded quartz grains poorly cemented with lime. They are cross-bedded and appear to occupy eroded channels.
>
> As the name implies, the Tohachi shale consists predominantly of argillaceous strata, arranged in groups 10 to 60 feet in thickness. The bedding of the shale, like that of the sandstone, is extremely irregular; sheets of sandstone and of earthy peat are included, and the beds replace one another within short distances along the strike. Fragments of carbonized and of petrified wood, sandstone concretions, flakes of gypsum and of sulphur probably of secondary origin, and lumps of mud are not uncommon. The shales are black, drab, blue, yellow, brown, and red in unevenly distributed streaks, some of which are continuous for several hundred feet and at a distance produce the effect of regular banding.
>
> Fragments of bone and *Unio* shells were collected from the sandstone bands of the Tohachi shale, and a variety of leaves and stems were found in the clay layers. On examination by T. W. Stanton, W. **H.** Dall, and F. H. Knowlton, the fossils proved to be not of diagnostic value beyond the fact that they indicate probable early Tertiary time. In composition and manner of deposition the Tohachi shale closely resembles the strata included in the Nacimiento group (basal Eocene) as described by Gardner (1910) .

To the above description there should be appended from the same page:

> The [Chuska] sandstone lies in a horizontal position and rests in most places on the eroded edges of Mesozoic strata—Chinle, La Plata, Mancos or Mesa Verde. At Chuska Mountain, however, it is underlain by a group of shales which in turn are underlain by truncated beds of Cretaceous age. Both the shales and the sandstone are assigned to the Tertiary and for purposes of description are distinguished as Tohatchi shale and Chuska sandstone. These Tertiary beds are unimportant factors in the groundwater problem with which **I** was chiefly concerned; they were therefore not studied in detail, and my conclusions regarding them are subject to radical revision.

Although the type sections are located less than 4 miles from a main highway, for over 35 years the highly tentative Tertiary age of the Tohatchi shale has been repeatedly, and even very recently, referred to in the literature. Because of the diverse lithology and revised spelling adopted by the Board of Geographic Names, the name of the unit is herein changed from "Tohachi shale" to Tohatchi formation.

The Tohatchi shale of Gregory's two type localities lies conformably above shales and sandstones of the Menefee formation (the original description quoted above included at least the upper 200 feet of Menefee) and may be divided lithologically into two units. The base of the lower cliff-making unit of the redefined Tohatchi formation has been arbitrarily placed at the top of the highest massive channel-sandstone in the Menefee (pl 5-A, and pl 11, sec 11). Above this point 400 to 850 feet of sandstones of the lower member of the Tohatchi are thin- to medium-bedded with about 50 percent shale interbeds. These beds are extensively crossbedded and crosslaminated, seldom more than 5 feet thick (in units from 5 to 30 feet thick, and are composed of medium- to fine-grained sandstones interbedded with silty gray clay-stones, carbonaceous shales, and lignites, which increase in carbon content from west to east and from bottom to top.

This lower member is overlain by an upper member at least 500 feet thick (top not exposed) of generally uniform, light olive-gray to yellow-gray (5Y5/2 to Y7/2), indistinctly thin-bedded, highly bentonitic shales which are carbonaceous near the base. Fossil bone, fresh water pelecypods (clams), wood fragments, gypsum flakes, and a few thin layers of dark-brown nodular iron-oxide-cemented sandstone appear at different horizons. These are probably not the "postMesaverde" beds which, although not described by Gregory in his text since he did not study them in detail (1917, p 75), are shown in the table (ibid, p 15) and graphic section (ibid, pl 3).

Vertebrate reptilian fossils collected at five localities ranging from middle Menefee to the middle of the upper bentonitic member of the Tohatchi formation (pl 11, secs 5, 11) were submitted to Charles Camp and Wann Langston, of the University of California Museum of Paleontology. Preliminary identification of an ornithischian dinosaur *(Hadrosauridae),* ganoid scales representing the alligator gar *(Lepidosteus),* and three turtle genera *(Aspideretes, Baena,* and possibly *Basilemys)* permit assignment of an Upper Cretaceous age to the entire sequence.

The stratigraphic position, lithology, thickness, and distribution of carbonaceous material suggest a tentative correlation of the lower member of the Tohatchi formation with the combined tongues of the Cliff House and Pictured Cliff sandstone diagrammed by Silver (1951, p 110). The upper bentonitic unit may prove to be the equivalent of the Fruitland formation, and possibly part of the Kirtland formation, since similar vertebrates also occur in these units. These correlations are also suggested on Figure 13.

This isolated section of uppermost Mesaverde has been preserved within the map area and for several miles farther north, owing to the combination of two factors: first, the wide, gently-plunging Nakaibito syncline, whose axis trends slightly east of north from Mexican Springs to the east of the Chuska Plateau, and second, the capping of Chuska sandstone of Chuska Peak and Plateau, which prevented its erosion. The base of the Tohatchi formation at its lowest exposed point is at an elevation of about 7,000 feet near the axis of the downwarp.

PLIOCENE (?) SERIES

CHUSKA SANDSTONE

The southern end of Chuska Mountain terminates at Chuska Peak, 3 miles west of Tohatchi. This high-lying plateau is underlain by upwards of 1,000 feet of massive, crossbedded, silica-cemented

Chuska sandstone which forms long escarpments, interbedded with weakly cemented and less resistant sandstone. This formation covers the northeastern quarter of Tohatchi quadrangle. Twin Buttes, an isolated outlier also composed of Chuska sandstone, appears south of Todilto Park. Landslide debris from the cliffs spreads out even more widely below the cliffs. The formation was named by Gregory (1917, p 80).

The Chuska sandstone overlies, commonly with marked angular unconformity, formations ranging from the Summerville upwards to the Tohatchi formation of the Mesaverde group. Under Chuska Peak, where the Tohatchi formation has very low dips, the contact is disconformable at an elevation of about 8,000 feet. Wherever exposed within the area, this unconformity is marked by a thin horizon of basal conglomerate containing large quantities of polished chert pebbles and petrified wood. It is generally from 2 to 15 feet thick, usually overlying a few inches to a few feet of pinkish or reddish siltstone. The conglomerate is composed of well-rounded and polished pebbles averaging from a quarter of an inch to 2 inches in diameter up to as much as 6 inches. At one locality, northeast of Todilto Park, their composition was 25 percent quartz and quartzite, 20 percent shale or slate, 20 percent black chert, 20 percent sandstone, 10 percent jasper, and 5 percent petrified wood, making up about 50 percent of the rock. The remaining 50 percent was grit-sized matrix composed largely of rounded quartz grains from 1 to 3 mm in diameter, some angular feldspar, and unidentified igneous fragments. Manganese concretions and cementation occur in several localities.

In a section east of Deza Bluffs, 3 miles north of Tohatchi, the lower part of the Chuska sandstone was measured by Wright[1], as follows:

	Ft
Massive crosslaminated sandstone	
Light green sand, sandstone, and clay	50
Chocolate-red clay	2
Buff to white sand and calcareous sandstone with sand crystals and honeycomb weathering	75
Light-green sand, sandstone, and shale, and chocolate-colored shale. Sandstone layers 2 in. to 6 in. thick, sand and shale layers ½ ft thick	25
White stratified sandy tuff with a few half-inch layers of sand	3
Buff sand and sandstone	15
Light-green sand and sandstone	20
Buff sand and sandstone, with 2-in. layers of salmon-pink gypsum. Contemporaneous deformation in sand layers	20
Chocolate-red shale, and buff and red calcareous sand	30
Red sandy conglomerate, with pebbles of quartzite, quartz, chert, sandstone, and slate	2
	242

Above the medium- to thin-bedded member of the Chuska sandstone the rocks are dominantly a buff to pale yellowish-gray (10YR8/2 to 5Y8/1), very thick-bedded, massive, fine- to medium-grained, cross-laminated arkosic sandstone. Quartz and feldspar grains are well sorted, well rounded, and subspherical. According to Wright, the

1. H. E. Wright, Jr., University of Minnesota, personal communication.

composition averages 74 percent quartz, 23 percent feldspar, and 3 percent chert and miscellaneous heavy minerals. Cementation is sporadic, usually being restricted to definite laminae, and consisting of opaline and chalcedonic silica. Crosslamination is pronounced throughout the upper part of the section, with dips in some places exceeding 35 degrees and averaging over 20 degrees, the direction of dip nearly always having a northern component.

Wright believes that the above characteristics are those of a sandstone of eolian origin, and that all but the lower 250 feet were deposited as great dune deposits, originating somewhere to the south or southwest.

The Chuska sandstone is penetrated and overlain by volcanic rocks in the vicinity of Washington Pass, 6 miles north of the area. Gregory (1917, p 80) believed it to be of Eocene age. Similar Tertiary beds occur between Gallup and Zuni 40 miles to the south. These have been described by McCann (1938) who correlated them with the White Cone sediments, and with the Chuska. The unconformity at the base of these sediments, the "Zuni erosion surface" of McCann, is believed by Reiche (1941) to grade westward into Dutton's surface of "great denudation" (Davis' "plateau cycle"), developed after the Cretaceous-Eocene uplifts. A small isolated sandstone mesa just south of U. S. Highway 66, 7 miles west of Lupton, Arizona, was examined by the writer and found to be lithologically similar to the Chuska sandstone, as are beds north of Chambers.

Widespread similar sediments interbedded with volcanic debris near White Cone, Arizona, contain fossils indicative of an upper or middle Pliocene age (Williams, 1936, p 130). "A huge species of camel, presumably of late Pliocene age," was collected by Childs Frick from gray sands with gravel and ash 5½ miles northwest of Jedito (60 miles west of Fort Defiance), and camel tracks in the sandstone were found southwest of Jedito. White Cone is about 12 miles south of Jedito.

On the basis of the above somewhat tentative evidence, the Chuska sandstone is believed to be of upper Tertiary and probably Pliocene age.

IGNEOUS ROCKS

The end of Cenozoic or Tertiary time was marked, on the Colorado Plateau, by volcanic eruptions. Basaltic lava flows poured out in the Hopi Reservation, and are preserved to this day. Elsewhere on the plateau erosion has destroyed most of the flows, but the feeding channels, or necks, remain standing. As nearly all of the igneous rocks in this area are more resistant to erosion than the surrounding sedimentary rocks, the necks, or plugs, form isolated, steep-walled cliffs that rise hundreds of feet above the plateau, giving it a distinctive scenic quality. From some of the plugs, such as Shiprock, igneous dikes radiate outward; other plugs are visibly connected by dikes, attesting the fact that the lava, or magma, advanced along fractures in the earth's crust, and drilled cylindrical channels only where it approached the surface.

Nine igneous plugs are located in the two quadrangles (see pls 3, 7-C, 8-C), and several dikes either connect them, or are so closely associated in space that there is reason to believe that a major fissure zone connects all, or most, of them at depth. The area mapped does not afford independent evidence to prove the late Tertiary age of the igneous rocks, but a short distance north of Tohatchi quadrangle, the Pliocene (?) Chuska sandstone is penetrated by several plugs which resemble in composition those of the mapped area.

The igneous rocks exposed in Tohatchi and Fort Defiance quadrangles have previously been examined by Pirsson (Gregory, 1917, pp 90-95) and Howel Williams (1936, pp 139-146). Although their observations cover the essential features adequately, the detailed mapping has brought to light additional facts that lend special interest to this group of igneous plugs. The presence of kimberlite tuff, in particular, is of general petrologic interest. The various rocks are described, and the geologic relations between them, as well as the structural features of individual plugs and dikes, are summarized.

Essentially, two groups of igneous rocks are represented: kimberlitic tuff, and minette, or trachybasalt, with associated agglomerates, breccias, and tuff.

Petrographic Description of Igneous Rocks, by Robert Balk and Ming-Shan Sun

Kimberlite tuff. On the map, kimberlite tuff and lapilli tuff have been separated, but it is believed that the two grade into each other. Kimberlite tuff is exposed in a bare, isolated hill, 150 feet high, a short distance northeast of the center of Buell Park (pl 4-C), as well as in a few low outcrops, about 1,000 feet east-southeast of that hill. The compact rock of purplish-brown, locally olive-green, color is crossed by innumerable crooked fractures, and shows in a fine-grained groundmass hundreds of well-rounded, grayish fragments of a fine-grained quartzite, ranging from 2 to 20 mm across. Larger fragments, up to 5 inches across, are rarer, and minute fragments are seen in all microscopic sections of the tuff.

Between the rock fragments are set individual, fresh crystals of bottle-green or light-brown olivine, pale-green or brownish enstatite with characteristic satiny luster, emerald-green chrome-diopside, and red or pink pyrope garnet. Less abundant are magnetite, titanclinohumite, clinopyroxene, ilmenite, apatite, and a serpentine mineral in minute fibers. The optical properties of the minerals are as follows (sodium light at 25°C):

olivine from kimberlite:	$N_X=1.649$	$2V=90° \pm 2°$
	$N_Y=1.671$	fa_{7-9}
	$N_Z=1.682$	
enstatite:	$N_X=1.660$	
	$N_Y=1.662$	
	$N_Z=1.673$	
chrome-diopside:	$N_X=1.671$	$Z \wedge c=45°$, $2V(+)=61°$
	$N_Y=1.677$	
	$N_Z=1.691$	

garnet:	N =1.746	color: dark-red
	N =1.744	color: pink
	N =1.744	color: amber-pink
titanclinohumite:	N_X=1.682	sp. gr. 3.364
	N_Y=1.684	
	N_Z=1.720	
antigorite:	N_Y=1.569	2V(−)=25°±
	N_Z=1.570	
green actinolite:	N_X=1.616	$Z \wedge c$=18°
	N_Z=1.635	

Titanclinohumite and chrome-diopside were analyzed chemically (table 15), and spectrographic data from chrome-diopside, pyrope garnet, green and brown olivine, and titanclinohumite are given in the subjoined Table 17.

Microscopically, the kimberlite tuff shows innumerable anhedra of olivine, between 0.2 and 3 mm in diameter, either fresh or in various stages of alteration to a mineral of the antigorite group (2V=0°-25°, optically negative, rarely positive) and locally associated with an unidentified mineral of appreciably higher birefringence, possibly sepiolite intergrown with talc (pl 9-A, B). Chlorite, showing first-order ultrablue interference colors, is also sporadically present. Bright-red iron oxide forms ill-defined shells or patches around many olivines, and appears generously in the groundmass in shapeless blebs, streamers, or stains. In slope debris washed from this hill and other tuff outcrops, black grains, 1 to 16 mm in diameter, proved to be titanclinohumite, but in only one thinsection was the mineral found in the rock. Possibly, titanclinohumite is an early alteration mineral of olivine, and drops out of the rock plates during sawing and grinding. Pyroxenes are also commonly altered to a mineral of the serpentine group, but the alteration has not gone as far as that of the olivines, and in all thinsections of kimberlite tuff there are many fresh olivines left. Pyrope garnets tend to drop out of the tuff during sawing, and only one crystal was preserved. It is colorless and free from strain birefringence. A few olive-brown, isotropic grains, 0.1 to 0.2 mm across, may be perofskite, picotite, or possibly a dark garnet. One grain shows fairly good cubic cleavage, suggestive of perofskite.

Clear olivines and garnets, 2 to 4 mm across, are fairly common in the ledges of this hill. In the low outcrops, 1,000 feet east-southeast of the hill, the largest crystals were found, measuring 11 mm (olivine), 7 mm (pyrope), and 14 mm (chrome-diopside). Some of the larger olivines are flat chips, showing good cleavage parallel to (010), and parting parallel to (100).

The chemical and mineralogical composition, the microscopic texture, and the occurrence of the rock as a plug leave no doubt that it is a kimberlite tuff. Silica in the analyzed specimen (table 15, n 1) is somewhat high for kimberlite (compare nos 2 to 7), but it is impossible to separate the smallest bleblike xenoliths of fine-grained quartzite from the tuff, so that a certain amount of contamination is unavoidable.

TABLE 15. CHEMICAL ANALYSES OF KIMBERLITES, RELATED ROCKS, AND 3 ASSOCIATED MINERALS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	47.50	43.27	30.66	45.48	47.36	45.56	30.80	38.78	54.32	58.02	47.77	47.50	35.34	54.17	52.40	54.07
Al_2O_3	1.38	3.49	2.86	3.16	5.03	4.40	4.60	6.85	9.87	12.12	8.64	9.62	0.00	1.43	1.73	2.08
Fe_2O_3	4.34	5.78	3.08	6.28	4.40	4.40	6.32	8.83	3.93	3.65	4.01	3.37	1.23	1.43	3.68	0.56
FeO	2.37	2.94	5.98	4.07	3.96	3.96	0.80	1.99	3.16	1.90	5.18	4.74	10.20	1.09	4.25	2.53
MgO	31.26	23.47	31.24	22.10	22.53	23.56	24.55	26.34	7.48	4.05	11.21	13.00	46.45	17.37	21.61	17.39
CaO	0.65	7.71	10.92	6.16	5.60	4.06	18.20	3.88	7.69	7.11	9.60	9.00	0.07	22.63	13.30	22.12
Na_2O	0.11	1.08	0.17	1.32	1.70	0.25	tr.	0.78	2.03	2.67	1.56	1.96	—		0.00	0.41
K_2O	0.37	2.57	1.23	4.84	2.63	4.49	0.82	2.56	7.28	6.96	4.17	3.28	—		0.00	0.00
H_2O+	10.88	4.45	3.01	2.02	2.74	3.51	6.33	7.85	1.10	0.54	3.38	3.90	1.14	0.23	1.20	0.04
H_2O-	1.15	1.50	0.93	2.56	1.34	2.40	0.60	1.95	0.07	0.05	0.49	0.90	0.02	0.10	0.44	0.06
CO_2	0.00	1.10	6.00	0.15	0.24	0.45	6.27	0.14	0.00	0.82	0.00	nil			0.15	
TiO_2	0.08	1.70	1.63	1.30	1.60	1.50	1.30	0.89	1.45	0.94	2.28	1.85	5.11	0.02	0.66	0.21
P_2O_5	0.02	0.10	1.64	0.08	0.04	0.20	0.11		1.15	0.77	1.21	1.05	0.12		tr.	
MnO	0.12	0.14	0.16	0.05	0.13	0.14	0.04		0.11	0.09	0.15	tr.	0.23	0.06	tr.	0.09
S			0.04	tr.	0.03	0.82	0.27								0.13	
F			0.04										0.06			
Cl			0.04													
Cr_2O_3			0.10			0.12	0.15						0.10	1.24	0.31	0.98
V_2O_3			0.02													
NiO			0.13	—	—	—	—								0.26	0.04
BaO			0.14													
SrO			0.08													
Li_2O			tr.													
−O			0.04										0.02			
Total:	100.23		100.06	99.57	99.33	99.82	101.16	100.84	99.64	99.69	99.65	100.17	99.95	99.77	100.12	100.58

1. Kimberlite tuff, Buell Park.* 2. Average of 8 kimberlites, South Africa (Williams, A. F., 1932, v 1, 146). 3. Fresh kimberlite, Dutoit's Pan mine (Holmes, A. and Harwood, H. F., 1932, 421). 4-7. Kimberlite, Premier mine, South Africa (Williams, A. F., ibid, 146). 8. Mica-peridotite, Prairie Creek mine, Pike Co., Ark. (Ross, C. S., 1926, 222). 9. Minette, core of Outlet Neck plug, Fort Defiance quadrangle, Ariz.-New Mex.* 10. Trachybasalt, top ledge, Buell Mountain, Fort Defiance quadrangle, Ariz.-New Mex.* 11. Dike "B" near Beelzebub plug, Tohatchi quadrangle, New Mex.* 12. Same dike as 11 (Williams, Howel, 1936, 166). 13. Titanclinohumite, Buell Park.* 14. Chrome-diopside, Buell Park.* 15. Chrome-diopside nodule, Jagersfontein mine (Williams, A. F., ibid, v 2, 379). 16. Chrome-diopside, Malips Drift Camp, Bushveld (Hess, H. H., 1949, 645).

* Analyst, H. B. Wiik (Helsinki).

TABLE 16. NORMS AND MODES OF IGNEOUS ROCKS

Norms of four analyzed rocks (Table 15):

	Kimberlite tuff Analysis 1	Minette Analysis 9	Trachybasalt Analysis 10	Minette Analysis 11
quartz	—	—	4.44	—
orthoclase	2.23	43.37	41.14	25.02
albite	1.05	9.96	22.53	13.10
anorthite	2.22		.56	3.89
leucite	—			
acmite	—	6.01		
wollastonite	.46	12.88	10.09	15.08
hypersthene				
$MgO.SiO_2$	67.80	10.30	10.10	12.20
$FeO.SiO_2$	.79	1.98		2.64
olivine				
$2MgO.SiO_2$	7.28	5.58		11.06
$2FeO.SiO_2$				
magnetite	6.27	2.55	3.48	5.80
hematite			1.28	
ilmenite	.15	2.89	1.82	4.41
apatite		2.69	2.02	2.69
calcite			1.80	
water	12.02	1.17	.59	3.87
	100.28	99.68	99.85	99.86

Modes of minette and trachybasalt:

1. Minette, dike in Buell Mountain: diopside, 10%; biotite, 1.2%; groundmass (sanidine, glass, ore, etc.), 88.8% (NA-2).
2. Trachybasalt, top of Buell Mountain, anal. 10: diopside, 23%; biotite, 2%; groundmass (mostly sanidine), 75% (NA-18).
3. Trachybasalt, base of Zilditloi lava: diopside, 11%; biotite, 2%; groundmass (much glass, and opaques), 87% (NA-45).
4. Minette, ring-dike, Buell Park: diopside, 18%; biotite, 1%; groundmass (glass mostly, with microlites), 81% (NA-9).
5. Minette, Fluted Rock: sanidine, 73.3%; diopside, 17.8%; biotite, 6.9%; magnetite, 1%; calcite, 1% (NA-16).

Lapilli tuff. This is the sole bedrock of Green Knobs, a small plug at the north base of Zilditloi Mountain; it also underlies most of the flat, alluvium-veneered bottom of Buell Park. In this region of tan and brick-red sandstones, the outcrops of uniformly pale-green lapilli tuff are striking features, and attract immediate attention. Lapilli tuff is a uniformly light-green, earthy, fragile, fine-grained rock, in which every surface reveals numerous xenoliths varying in size from small fractions of an inch to blocks over one foot on a side. Apart from this greater proportion of inclusions, the chief difference from kimberlite tuff is that fresh olivines, chrome-diopsides, and garnets are relatively rare in the lapilli tuff. Many large surfaces show none at all.

Microscopically, the rock shows the same texture as the kimberlite tuff, but, in contrast with that rock, nearly all olivines in the lapilli tuff have been altered completely, the antigorite masses seem to be free from the strongly birefringent mineral mentioned above, and iron-oxide stains are virtually lacking. Magnetite or ilmenite in irregular

TABLE 17. SPECTROGRAPHIC ANALYSES OF KIMBERLITE MINERALS FROM BUELL PARK, BY OIVA JOENSUU, UNIVERSITY OF CHICAGO

	1 Chrome-diopside	2 Olivine, brown	3 Olivine, green	4 Garnet, amber	5 Garnet, pink	6 Garnet, dark red	7 Titan-clino-humite
CoO	30	140	160	75	85	X	150
NiO	23	4000	4600	35	30	15	3200
ZrO_2	X	X	X	X	X	X	X
V_2O_3	670	X	X	200	160	300	120
Cr_2O_3	~1%	40	20	1200	2200	~5000	600
La_2O_3	X	X	X	X	X	X	X
MoO_3	X	X	X	X	X	X	X
Y_2O_3	X	X	X	X	X	X	X
BeO_3	X	X	X	X	X	X	X
Ga_2O_3	~10	X	X	~10	~10	~10	X
SnO_2	X	X	X	X	X	X	X
PbO	X	X	X	~10	X	~10	~50
BaO	90	15	20	X	X	X	X
SrO	130	20	X	X	X	X	X
Major constituents:							
Na	high	+	+	+	+	+	+
Ti	++	+	+	++	++	++	<u><u>high</u></u>
Fe	high	high	high	high	high	high	high
Al	high	++	++	<u>high</u>	<u>high</u>	<u>high</u>	++
Si	high	high	high	high	high	high	high
Mg	high	<u>high</u>	<u>high</u>	high	high	high	<u>high</u>
Ca	<u>high</u>	++	++	high	high	high	++

All figures are in parts per million. ~ means approximately. X means no line present, concentration is below limit of detection, which is: Co, Ni, Cr, Mo, Be, Bi: 5 ppm; V, L, Sr, Pb, Sn, B, Ga, Ge: 10 ppm; Zr: 50 ppm; As, Sb: 200 ppm; Na: 500 ppm. + means traces (0.001 - 0.05%); ++ means 0.05 - 0.5%; high means over 1%; <u>high</u> means 10 - 20%; <u><u>high</u></u> means over 20%. Not present (or below limit of detection): Ge, B.

blebs and groups of distorted prismatic grains were noted as more abundant than the red iron oxide. This may explain why the lapilli tuff lacks the brownish hues of the kimberlite tuff. Even specimens that seem to be free from xenoliths show, under the microscope, many minute fragments of foreign rocks, but commonly with indistinct borders, as if the smallest xenoliths were in process of merging with the surrounding antigoritic groundmass.

The layering of the tuff, and the nature of the xenoliths, will be discussed below.

Minette and trachybasalt. These two names are employed for rocks that are indistinguishable in hand specimens. The term minette refers to intrusive rocks, and trachybasalt to extrusive ones. Therefore, when dikes and intrusive plugs are concerned, the igneous rock is called minette; but when there is suggestive evidence that a plug had reached the surface of the earth, and the lava had come in contact with the atmosphere, the term trachybasalt is preferable. Although the use of two names encumbers the terminology, it helps to distinguish erosional stages in the history of the igneous rocks.

Minette. This rock builds up Fluted Rock; the ring-dike and a group of coalescing dikes and lenses in Buell Park; Outlet Neck; a short dike, 1 mile south-southwest of Outlet Neck; The Beast; several dikes east and north of The Beast; an unnamed plug, 1 mile northeast of The Beast; Beelzebub; and Black Rock, just south of the southern border of Fort Defiance quadrangle. In all these dikes and plugs minette is associated with breccias and tuffaceous phases, and the proportions of these vary from place to place. On a map of larger scale the breccias could have been shown separately, but only at Buell Mountain, on the southern slopes, do breccia and agglomerate occupy areas of appreciable size. As a special color symbol would have been required between the minette dikes, it was omitted, since it would have obscured the relief features of the photomosaic.

Fresh minette is a fine-grained to aphanitic, dark-gray or nearly black rock, generously sprinkled with brownish-black phenocrysts of biotite, about 1 mm in size, and more sparingly with greenish-gray clinopyroxene, 3 to 5 mm across. Occasionally phenocrysts of either mineral may exceed 1 inch in length. In most outcrops the rock is compact, but at Fluted Rock, Outlet Neck, and a few other places, layering is pronounced. Vesicles, from microscopic dimensions to cavities several inches across, are irregularly distributed, and vesicular minette may pass into tuff, breccia, or agglomerate.

The microscopic features have been adequately described by Williams (1936, pp 149-153). A groundmass of pale-brown glass, small plates of biotite, feldspar, and iron ore, is thickly crowded with crystals of diopsidic pyroxene and biotite, seriate from minute blebs to subhedral or euhedral grains of appreciable size (pl 9-E). Patches of glass commonly are enclosed in the pyroxenes, and their borders may be corroded and embayed by the groundmass. Pale-green fringes, cores, or both, indicate oscillation from diopside to aegirite during the growth of the pyroxenes. Pleochroism, deep-brown to pale-brown or tan, and optical properties ($N_y = 1.670 \pm 0.002$) characterize the micas as intermediate between biotite and phlogopite. The margins of many biotites have been converted into shells of iron oxide. The amount of glass in the groundmass varies. It makes up nearly one-half of the groundmass of the ring-dike at Buell Park, but dikes in Buell Mountain have very little. Likewise the amount of sanidine, the only feldspar that could positively be identified, varies inversely with the amount of glass. The groundmass of the Outlet Neck minette has some minute grains only, but at Fluted Rock sanidines have grown to over 2 mm in length and enclose poikilitically all other minerals (pl 10-A,B).

Leucite is alleged to occur both at the Buell Park ring-dike (Williams, 1936, p 142) and at a dike one-half mile southwest of Beelzebub (ibid, p 152, 154). Although its presence is highly probable, and of great scientific interest, it appears in none of the specimens and thinsections prepared in connection with this study. Olivine has been found as a rare mineral in some of the minettes (ibid, p 151), but again the writers have been unable to identify this mineral in any sample. Plagioclase may occur in traces in the fine-grained groundmass of some minettes; a small amount appears in the norm (table 16), but it has not been positively identified. Accessory minerals of the minette are apatite, iron ore, and minute needles in sanidine that may be amphibole. Vesicles in the minette, especially near contacts with wall rocks, are filled with calcite.

The minette of most of the plugs in the area is intimately mixed up with vesicular phases that range from compact, firm minette, with a moderate amount of small vesicles, to highly porous mixtures of minette fragments, surrounded by ashes, quartz sand derived from sandstone wall rocks, and larger blocks of fractured and recemented breccia. Here and there larger cavities appear in these mixtures. At the northeast base of the minette-breccia dike, 1 mile southwest of Outlet Neck, a cavity measures 30 by 12 feet, with a ceiling 4 feet high, from which many calcite crystals project into the cave. Minette may enclose fragments of breccia, but breccia masses, in turn, are cut by minette dikes in several localities. One may assume that relatively quiet outflow of minette and violent outbursts of water vapor and other volatiles alternated many times.

The temperature of the minette was hot enough to convert some of the sandstone into mixtures of quartz grains and glass ("buchite"). Good examples are exposed at Outlet Neck and Fluted Rock. At both places the partly vitrified sandstone exhibits beautiful columnar structure. At Outlet Neck the vitrification is later than small faults which displace the sandstone beds by fractions of an inch. Xenoliths of silt-stone at Fluted Rock have been converted into black buchite, composed of clastic quartz grains embedded in glass. In this rock numerous greenish interpositions appear, 1-2 inches across, with brown shells. The greenish rocks are glass-free siltstone, and in the brown shells there appears a finely fibrous, brown mineral that is possibly a chlorite, charged with iron oxide. A spectrographic analysis of the xenoliths shows that zirconia, strontium oxide, and barium oxide are surprisingly abundant (400 parts per million, over **1** percent, and over 20 percent, respectively) in the brown shells, are fairly abundant in the surrounding siltstone, and relatively low in the greenish cores. High-temperature contact minerals may be present in these rocks, but the grains are so minute that identification was impossible. The effect of the heat on fragments of sedimentary rocks appears to vary from place to place. Although many xenoliths at Fluted Rock show considerable vitrification, thinsections of two pieces of fossil wood from the same ledges show no coarsening in the microscopic texture of the chalcedonic quartz.

Trachybasalt. As already stated, the rocks mapped as trachybasalt do not differ in mineral composition from minette. The highest ledges in Buell Park are underlain by pale-gray, fine-grained, locally layered rocks showing biotite phenocrysts and, more rarely, diopsides of the same character as those in the minette. The ledges that form the top of Zilditloi Mountain are darker, locally aphanitic, and contain much glass in the groundmass (pl 10-C). As stated by Williams (1936, pp 142, 154, 155), the Buell Park rocks are largely a felt of slender laths of sanidine, showing good fluxion structure, whereas, at Zilditloi Mountain, the proportions of sanidine, biotite, and diopside are about the same as those in normal minette dikes. Although the glass contains so many interpositions that its index of refraction could not be determined accurately, it is believed that its composition is close to that of potash feldspar.

Although, in the writers' opinion, it is not certain that the lava at these two mountain summits had reached the earth's surface, and had poured out over it as true lava flows, there is no doubt that the material at these points has approached the late Pliocene (?) surface more closely than anywhere else in the mapped area. Since Williams had the benefit of much greater acquaintance with contiguous lava flows, such as the one at Sonsela Butte, and thought that at Buell Park and Zilditloi Mountain surface flows are present, the writers have tentatively adopted his interpretation. Some observations that have a bearing on the problem, will be given below.

A more detailed study of the various igneous rocks in this region may make changes in the terminology desirable. For instance, the rocks that compose the highest ledges of Buell Mountain, with their potash-soda ratio of 6.96:2.67, are almost certainly "potassic biotite-diopside trachyte," and a cupolalike mass of the same rock underlies much of the southern part of Buell Mountain (pl 9-F). However, the contacts of these trachytic phases are not everywhere well exposed. Their darker portions are difficult to distinguish in the field from minette. Until many more specimens have been studied optically and chemically, it seems best, therefore, to retain Williams' term trachybasalt for the rocks of both Buell Mountain and Zilditloi Mountain.

Description of Individual Areas

Kimberlitic and composite plugs. Buell Park. This large composite plug is in many respects the most interesting one in the area (pl 12-A—in Pocket). The flat, alluvium-veneered bottom of the park is, for the most part, underlain by lapilli tuff. A vertical contact with the Cutler sandstone is exposed in a short, south-draining ravine, at the northwest base of Buell Mountain. The boundary, exposed over 30 feet, trends north-northeast to northeast. Sandstone showing no contact effects adheres to the tuff, and at a few places protrudes slightly into the tuff. Three feet southeast of the contact, entirely within the tuff, is a slip zone. It dips at 70° SE, and is coated with a snow-white gouge, one-half inch thick, striated down the dip of the plane. At the contact exposure, and also a short distance north of the same ravine, short, irregular tuff dikes extend from the main mass of the tuff into the sandstone. In at least one place, a dike is flanked and partly covered by sandstone, suggesting that this portion ended upward blindly. The tuff-sandstone contact is exposed also northeast of Buell Mountain, and again the boundary is vertical, but showing minor indentations in plan.

On the northwest slope of Buell Mountain, the lapilli tuff is layered, and dips 15°-30° SE into the plug. About 1,000 feet east, in a high cliff on the northeast slope of the mountain, tuff layers lie nearly horizontally. Nowhere else in Buell Park was layering clearly visible, but it is probable that if exposures were better, a system of inward-dipping layers, like a stack of saucers, could be seen. This is, at least, strongly suggested by the corresponding features at Green Knobs.

Along the southwest contact, the boundary of the tuff can be drawn with an accuracy of about 10 to 15 feet in several places, and must be vertical or very nearly so. This can be inferred also from sporadic outcrops on the east side, for instance, on the north bank of the canyon that drains Buell Park, and in a cliff about one-half mile north of the point where the east-west, fair-weather road leaves Buell Park on the east side. Nowhere along the contact is there any suggestion that the tuff plug has slipped past the surrounding sandstone along a fault. In view of the indented nature of the contact surface and the adherence of the contrasting rocks, a fault would have to lie either within the sandstone, or within the tuff plug, but leaving an outer shell in its original position. Though exposures are not as good as one might wish, they are thought to be adequate to exclude this possibility. The lapilli tuff at Buell Park is without doubt in its original position with reference to the sandstone envelope, and the plug does not appear to have been raised nor dropped after the consolidation and final compaction of the tuff.

The kimberlite tuff, with its larger proportion of coarse, fresh crystals, could be a slender cylindrical mass that fills a central, or axial, channel in the plug. Contacts with the surrounding lapilli tuff, unfortunately, are concealed, so that it is unknown whether the two phases of the tuff are essentially one mass, or whether the lapilli tuff had been consolidated and compacted prior to the intrusion of the coarse crystal tuff. The greater erosional resistance of the kimberlite tuff is due, presumably, to the greater proportion of crystals, aided by silica precipitated along innumerable minute fractures. This may also be the reason why the lapilli tuff that surrounds the ring-dike weathers out as a somewhat more resistant rock than the green, earthy tuff. Several ledges on the north side of the ring-dike show thin, white films in the lapilli tuff, and here the ring-dike was probably the source of the silica and iron oxide.

The ring-dike that swings through 115 degrees of arc, and the several minette dikes in the southern slopes of Buell Mountain, are all later than the kimberlite tuffs. But, as will be shown, there is reason to believe that the intrusion of minette and trachybasalt was closely related both in time and origin to that of the kimberlite tuffs. The ring-dike, 3 to 30 feet thick, cuts through lapilli tuff along its entire curved contact. This dike dips vertically, but at the easternmost outcrops it dips (westward) into the plug at 57 degrees. The downward prolongation of a ring-dike is a cylinder or steep cone with vertical axis, whereas an inward-dipping dike could be called a cone sheet, after the Scottish examples, and might be assumed to have started from a small orifice, near the axis of the tuff plug. The true shape of this dike cannot be inferred with accuracy, but both possibilities should be considered.

Whereas the ring-dike is, essentially, a curved plate of compact, firm minette, the dikes at Buell Mountain have been preceded and followed by violent eruptions of ashes and coarse breccia, which constitute many picturesque crags near, and between, the individual dikes. In this incompletely consolidated mass, the dikes form short plates, irregular lenslike masses, and connecting bodies that lie flat in places, vary their shape, and may have approached the then surface so closely that the very highest outcrops, near the summit of Buell Mountain, represent perhaps the base of a flow, or the root of a surface volcano. Locally, at any rate, the lava rests on a level floor of breccia, and columnar joints stand nearly vertically on the south face of the summit cliffs, suggesting a flat cooling surface. The entire breccia-minette-trachybasalt complex appears to rest like a club- or steep funnellike mass on, or between, lapilli tuff, but exact boundaries are impossible to draw in the talus. Conceivably, the nearly trachytic composition of the rock in the top ledges reflects the effect of differentiation at the higher levels in the magma that gave rise both to the minette and trachybasalt. A second mass of relatively light-gray trachytic rock that underlies the domelike southern summit of Buell Mountain is, however, a small plug, and a steep contact is exposed on its northwest flank.

Not a single outcrop of igneous rocks was seen on the slopes beyond the rim of Buell Park. However, as the abundant olivines, pyrope garnets, and chrome-diopsides in anthills attest, the kimberlitic tuff must have been scattered over a radius of at least 9 miles from Buell Park (fig 2). Were it not for the unusual resistance of these minerals, the subsequent erosion would have removed all the evidence of the explosive volcanism. How thick the original ash may have been is unknown; nor can one tell how high above the present land surface the ash-covered plateau has stood. As an estimate, an interval of some 700 feet may be suggested.

Green Knobs. This plug is composed entirely of lapilli tuff (pl 12-B —in Pocket). The wall rocks are, on the west, upper Chinle shales with a ridge-forming pellet conglomerate bed; on the east, the Wingate and Entrada sandstone. For a distance of about 200 feet the southeastern contact of the plug is exposed, dipping 72-85 degrees inward as the curved surface of a gigantic, steep-sided funnel. Locally, the surface is striated down the dip, or very nearly so. As at Buell Park, contact effects on the sandstones are lacking, except for a deeper red of the normally tan and pinkish rocks. Calcite poikiloblasts in the sandstone cement are not a contact feature, since they can be seen in many other places, far from igneous rocks.

This plug exhibits beautifully the saucerlike arrangement of tuff layers (pl 12-B—in Pocket). At the contact, they are parallel to the steep surface (pl 7-C), but within 120 feet the dips flatten to 30 degrees and 20 degrees. Near the center, the layers are about horizontal. The structure is peculiar in that a hand specimen or single block of the tuff appears massive, but all larger surfaces reveal the layering by the manner in which the numerous xenoliths are arranged. Nearly all are single fragments, but differently spaced along parallel planes. The tuff between them shows elusive, fine cracks parallel to these layers, probably owing to films of particularly fine antigorite fibers. However, the rocks are so fragile that it was impossible to verify this by examination of thin-sections. This plug shows a particularly wide range of rock types among the xenoliths, which include peridotites. They will be discussed jointly with those of Buell Park following the description of the plugs.

The origin of a synclinal, inward-dipping system of tuff layers has been noted and discussed by many observers (Williams, 1936, pp 141143; Cloos, 1941, pp 719-723, 775-777, 796; Shoemaker, 1953, p 24). There appears to be agreement that the flattening of layers, which at the pipe contacts are nearly vertical, is due to a downward sagging of the tuff. However, whether this movement registers merely the compaction of an originally gas-charged mixture; whether it is due to more vigorous downward motion of larger parts of the plug, caused perhaps by violent discharge of volatiles; or whether the entire igneous mass has slipped down, after the manner of the Scottish examples of cauldron subsidence, must be examined with care. Both at Buell Park and Green Knobs, the tuff layers are crossed by white joint veneers composed of quartz, calcite, and a serpentinous mineral, also by pale-green veneers of antigorite along innumerable occult fractures and cracks. Thus, the layers must have acquired their present arrangement essentially during the final stages of the eruptive cycle. In agreement with this, there is no fault at the plug contacts, but tuff and sandstone are evidently in primary, undisturbed contact. Numerous slip zones, however, dissect the tuff near the contacts with the sedimentary rocks. They are well developed at Buell Park, where they are coated with thick plates of sepiolite (Nx =1.512, Nz =1.521). Slabs over a square yard in size weather out near the western contact of that plug, and smaller plates have formed at other contact exposures in both necks. Wherever these veneers are in place, the fibers plunge parallel to the dip of the planes and give the impression of striations. Actual grooves, recording relative movement of the adjoining surfaces, may also be developed, and follow the same direction. It was, unfortunately, impossible to ascertain the direction of these movements from visible displacements of any identifiable features on opposite sides. If the one-sided roughness of the surfaces is tested, nearly all appear to be upthrusts; although this method is not necessarily reliable, it receives support from the orientation of the fractures. Both at the eastern contact of the Green Knobs and on all sides of the Buell Park plug, the planes dip into the plug at angles of from 85 degrees to about 50 degrees. Rarely do they reach the contact, but are concentrated in a tuff zone, about 100 feet wide, near the contact.

If even the small and weathered contact exposures of the tuff plugs show so many fractures in uniform orientation, it could be inferred that the entire contact zones are penetrated by inward-dipping fractures, and that they opened early enough during the cooling of the tuff to allow the growth of substantial veneers of sepiolite among them. The dominant inward dip of the planes provides a strong suggestion that they opened in response to shear stresses that tended to raise the plug with reference to the wall rocks, not to lower it. It is believed that the actual movements on these funnel joints were probably very small;

however, a joint system commonly records the tendency of rock masses to move, rather than a prodigious dislocation along such planes. To that extent, the sepiolite fractures are believed to be reliable.

The occurrence, side by side, of a synclinal system of tuff layers and these funnel fissures may seem to be contradictory. Yet it is no more so than the alternating manifestations of eruption and subsidence in active volcanoes. The carefully studied eruption of Vesuvius in 1906 may serve as an example. Apart from elevating the entire base of the volcanic edifice, so that the shore line of the Gulf of Naples was raised, its net result was an addition of some 20 million, or more, cubic meters of lava to the earth's surface (Perret, 1924, pp 89, 143), not counting the prodigious volume of ash and scoria strewn over the countryside. Yet Perret devotes an entire chapter to subsidence phenomena (ibid, pp 113-118). In addition, he describes the temporary or local collapse of hot ashes owing to emission of gas (pp 89, 90), the lowering (p 66) and temporary collapse of the entire top of the volcano (pp 94, 95), internal avalanches owing to gas and vapor discharge (pp 101, 102), and large areas that collapsed by reason of the draining of supporting lava through hidden channels (p 96). The dilated condition of the hot ashes gives the material mechanical properties and mobility compared by Perret with that of quicksand (pp 89-91), and the adjustment of this loose material produces the large-scale stratification so commonly observed on the crater slopes (p 55, fig 41). It seems self-evident that the same sorting and layering will take place on the inner walls of the conduit, though it is here, of course, concealed from the eyes of observers, and becomes visible only after a long period of erosion and quiescence of the volcano.

It is believed, therefore, that numerous features in volcanic plugs may indicate relative or absolute sagging of the igneous fill with respect to the surrounding crust; but care should be exercised not to exaggerate the magnitude of these movements. The syndinal layering of the tuff, as observed at Green Knobs and, locally, at Buell Park, seem the inevitable form of mechanical adjustment of the erupted loose ash and lapilli to a gradual compaction after the associated volatiles had been expelled, and we do not know of any observed feature that compels one to assume that either of these plugs has substantially subsided during, or after, the consolidation of the volcanic rocks.

Though there appears to be no valid evidence supporting the assumption of wholesale subsidence of the plugs, one other feature should be mentioned that could be interpreted as suggesting that locally some of the wall rocks have subsided. The eastern part of the Green Knobs tuff plug is surrounded by the Entrada and Summerville sandstones. The contact is not a continuous cliff, as at Buell Park, but a curved depression, east of which is a large forested slope with many large, loose blocks of Summerville sandstone. In the distance, the undisturbed cliffs show horizontal beds, but some of the blocks near the tuff contact are so large that one might consider this an area where the Summerville formation was perhaps shattered by the intrusion of the plug, and crumbled into these haphazardly oriented blocks. To be sure, there is no tuff between them, and the tumbled rocks could as well be a cliff-fall or landslide, though these are generally absent in the outcrop area of the Summerville formation.

At the west end of the contact exposures, the tuff is accompanied by tan sand in miniature dunes. Amidst this loose sand is a poorly consolidated mass of a peculiar tan sandstone with many small brown fragments. The rock is cavernous and hard to interpret. It could be a mass of drifting sand cemented very recently, like the tufa deposits south of Sawmill. It could, however, be assumed that this is a block of a strati-graphically higher sandstone. It is impossible to match this rock exactly, but the rocks that approach it more closely than others are in the Morrison and lower Dakota (?) formations, several miles away, and about 700 feet above the top of the Entrada sandstone. The contact of this sandstone with the tuff is not directly exposed, and the provenance of the rock is obscure.

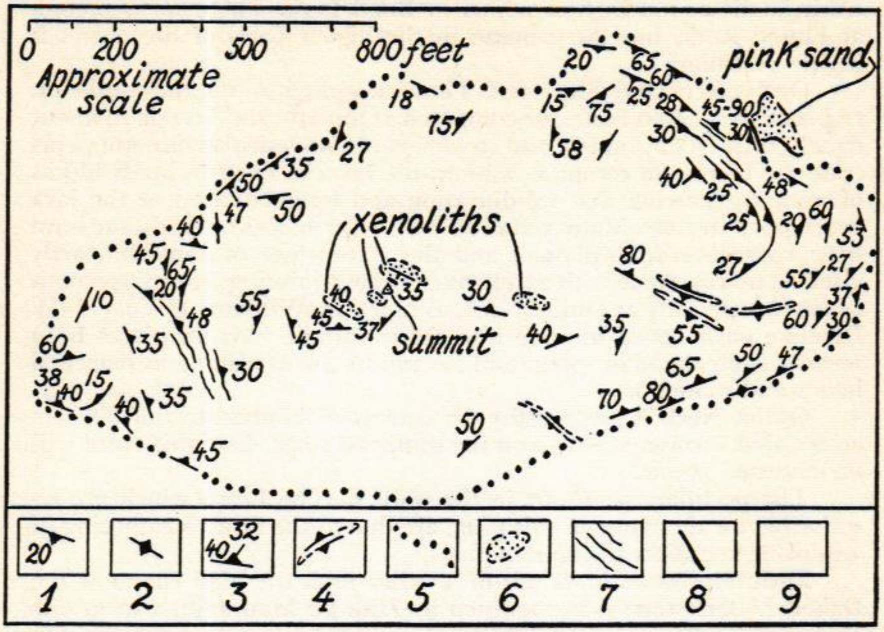
Lapilli tuff plug north of Zilditloi Mountain. This small plug, with a diameter of only 150 feet, is poorly exposed. Its borders are concealed and the plug has no surface expression (fig 11). Only green lapilli tuff was seen.

Minette plugs. Fluted Rock. This plug, about 2,000 feet (east-west) by 1,000 feet (north-south), stands at the western border of Fort Defiance quadrangle, 5 miles west-southwest of Sawmill. It is composed of vesicular minette, of medium to light greenish-gray color, and of normal mineral composition. The plug rises about 400 feet above the level of the surrounding plateau, presenting nearly vertical, conspicuously fluted cliffs on all sides. The contact is concealed, except for one small exposure on the east side, where a small mass of pink sand, one foot from the minette cliff, represents in all probability a mass of lower Chinle sandstone, which here, with the Shinarump conglomerate, forms a thin featheredge on top of the De Chelly sandstone.

A short distance south and east of the summit, the minette encloses xenoliths of sandstone and siltstone, in part vitrified to buchite. Fragments of fossil wood leave no doubt that at least some of the rocks are lower Chinle sandstones.

The flat-topped plug exhibits planar alignment of the minerals on a large scale (fig 14). The layers dip inward at intermediate angles, thus resembling the arrangement of the lapilli tuff at Green Knobs. In several places the layers are crossed by steep, dikelike minette bodies with indistinct contacts and terminations. Near the east end of the plug, minette layers are folded almost to isoclinal position. The columns evidently formed fairly late during the solidification of the plug. On the southwest border they dip at high angles southwestward, regardless of several curves and synclinal folds of the layers that are plainly exposed in the vertical cliffs.

In three places, at the southwestern, northwestern, and northeastern border, the exposed layer surfaces show lineation of the constituent minerals. The delicate structure is caused by slight differences in the amount of sanidine in contiguous areas, so that the *eye* can distinguish parallel streaks of slightly varying shades of pale greenish-gray. In each



OUTLINE MAP OF FLUTED ROCK, SHOWING STRUCTURE OF A PLUG OF MINETTE SURROUNDED BY CHINLE FORMATION.

Explanation of symbols: 1. Strike and dip of layers of minette. 2. Vertical layers. 3. Layered minette, with lineation plunging 32 degrees within the plane of the layers. 4. Vertical dikelike schliere of minette. 5. Approximate border of the plug. 6. Xenolith of sandstone in the minette. Xenolith directly northeast of top of Fluted Rock shows sandstone beds dipping 35 degrees southwest. 7. General strike of layered minette. 8. Exposed contact of plug. 9. Outside of plug is Chinle shale and sandstone.

Figure 14

locality the tracts parallel closely the steepest directions of dip on the layers of minette; in view of the geometry of the plug, it is probable that at these three contact zones the solidifying minette was drawn out straight up along the flow planes. This is to be expected in a plug, where the direction of greatest lengthening is ordinarily upward.

The flat-topped plug (pl 7-D) has been called a sheet, or laccolith (Gregory, 1917, p 106; Williams, 1936, pp 139, 157), but the evidence is, at best, inconclusive. The contacts of the minette with the xenoliths are so incompletely exposed that no flat surface can be constructed to represent the top of a laccolith. It cannot be a sheet in view of the steep dips of the flow structure. It might be a bulbous, vertical plug, flaring funnellike outward and upward as it approached the Pliocene (?) surface, resembling in this regard the masses of minette and trachybasalt at the highest points in Buell Park. There is no breccia at Fluted Rock, but the minette in the higher parts of the ledges is highly vesicular.

Outlet Neck and The Beast. These two plugs, south and southeast, respectively, of Red Lake, are composed of minette and breccia in about equal parts. Dikes, lumps, and streamers of nonvesicular minette penetrate the breccia in complex fashion; the breccia, in turn, holds blocks of minette, showing that solidification and fragmentation of the lava overlapped in time. Many xenoliths and larger blocks of sandstone have been contact-metamorphosed, and the snow-white or pinkish, partly vitrified masses, some with excellent columnar jointing, are conspicuous features, especially at Outlet Neck, as noted by Williams (1936, p 145). Dikelike offshoots of minette into the sandstone have in places been severed from the main plug, and lie amidst the sandstone as detached lenses and plates.

Outlet Neck is noteworthy for a mass of kimberlite tuff, 60 feet across, that forms a xenolith on the southeast slope. Its significance will be discussed below.

The peculiar reentrants in the walls of The Beast, which are responsible for the name of this plug, are due to the faster weathering of sandstone xenoliths in the minette.

Zilditloi Mountain. South of Todilto Park the high cuesta of the Dakota (?) sandstone is surmounted by Zilditloi Mountain, a steep pile of trachybasalt, with well-developed outward-plunging columns. On the southeast and north, the lava rests on pyroclastics and tuff, and the exposed contacts, as well as feeble layering in the trachybasalt, dip at 35-40 degrees into the mountain. On the west and east, sandstone and conglomerate are exposed a short distance below the lava, but actual contacts are concealed by talus. However, both on the western and northwestern base of the summit cliffs, the rock is faintly layered, and the dip is at 10°-30° E and SE into the mountain. This structural similarity with Fluted Rock and Buell Mountain suggests that Zilditloi, too, is a bulbous or funnel-shaped upper ending of a plug, which approached the surface so closely that it could be regarded as the throat of a former volcano. Whether the base of the ledges truncates the sedimentary formations, as Williams assumed (1936, p 146), or rests more or less conformably either at the top of the Morrison, or within or on top of the Dakota (?) sandstone, must likewise be left undecided. These strata resemble each other so much that they cannot be distinguished with certainty where small outcrops are weathered and strewn with basalt talus.

An additional reason for regarding Zilditloi Mountain as the widened end of a plug is the abundance of xenoliths in this rock. As one climbs the slopes of this mountain, it is difficult to pass a group of talus blocks without having his attention arrested by the multitude of dark inclusions, mostly of pyroxenite, but also of gabbro, norite, and diorite; bottle-green olivine masses are also fairly common. Granitic and gneissic xenoliths, although by no means absent, are rarely as numerous as the dark ones. The pyroxene in most of these seems to be a hedenbergitic diopside (Nx=1.689, Ny=1.695, Nz=1.713; Z ^c=48°; pleochroism: X, pale green; Y, olive-green; Z, smoky brown), although, without chemical analysis, the exact composition is, of course, somewhat uncertain. Orthopyroxenes were seen only in norite xenoliths, in agreement with Williams' observation (1936, pp 146, 162). Olivine was separated from several inclusions. The crystals are fresh, and range in composition from fa_7 to fa_{il}, thus including the range of composition of the kimberlite olivines.

Other plugs and dikes. Little need be said about the remaining plugs and minette dikes. Beelzebub and the minette plugs and dikes northwest and northeast of Zilditloi Mountain resemble The Beast in that a generous amount of breccia is associated with minette. Nearly all the dikes that extend from The Beast east and north are vesicular, dark-gray rocks. In contrast with the plugs, the dikes do not appear to have caused any contact effects in the surrounding sandstones. A minette dike, said to occur west of Red Lake (Gregory, 1917, p 93), has not been located. The dikelike masses, 1 mile south of Outlet Neck, and Black Rock, southeast of Fort Defiance, contain mostly breccia, and only smaller irregular masses of highly vesicular minette. Xenoliths present in them are relatively small, pale greenish-gray blebs of quartz, chlorite, and other minute, unidentifiable minerals. Fragments of Chinle sandstone and shale are subordinate, some being vitrified.

Hypothetical Relationship between Kimberlite and Minette

General statement. The map of the two quadrangles shows that nearly all igneous rocks crop out along an east-west-trending zone, extending from Fluted Rock on the west to the longitude of Beelzebub. The foregoing description has shown that kimberlite tuff is not only closely associated in space with minette and trachybasalt, but that the igneous activity began with eruptions of kimberlitic tuffs and was followed by minette intrusions which, in all probability, reached the level of the earth's surface a few hundred feet above the present surface. This ancient surface must also have been reached by the kimberlite eruptions, as evidenced by the wide area over which olivine, pyrope, and chrome-diopside crystals have been scattered. The instructive exposures of Buell Park and Outlet Neck reveal an even closer relationship between the two rocks: the geometry of the cylindrical kimberlitelapilli tuff plug has controlled the shape of the ring-dike, has confined the great cluster of minette dikes of Buell Mountain, and at Outlet Neck has guided a minette plug on its upward motion. It is almost certain that this plug has followed a kimberlite predecessor, and has dragged fragments of it upward.

To appraise the meaning of this association is, by the nature of the situation, beset with difficulties, and it must be realized that an interpretation of this kind remains hypothetical. Nevertheless, problems of igneous rocks and their origin are commonly pieced together by combining the scattered data of various regions and tracing systematic relationships, until at least the broad outline of a mechanism can be seen that may have been at work. The present area provides one additional clue, in the nature of some cognate xenoliths, toward the possible genesis of the rocks.

Xenoliths of the kimberlitic tuff. It is useful, following the South African terminology (Wagner, 1914; Williams, A. F., 1932), to distinguish foreign and cognate xenoliths. Among the foreign ones fine-grained quartzites and quartzschists exceed all others in quantity. The majority are so similar to the quartzite exposed in Blue Canyon Wash that they probably represent the same formation. Locally abundant are nearly black, fine-grained, slightly schistose members of the same group, cemented by opaque iron ore. A variety of granites, gneissic granites, and darker, dioritic medium-grained rocks are encountered likewise in all three lapilli tuff plugs. Among them there is a peculiar, coarse-grained, porphyritic type in few, but relatively large, blocks. It appears to have been shattered during the passage in the channels and, where in contact with minette, thin pockets and films of the dike rocks penetrate these blocks, corroding the groundmass of the granite, and causing the large orthoclase crystals to become cloudy and altered. Fingers of brown, partly devitrified glass, carrying aegirine, iron ore, and sanidine, were seen in all thinsections.

Fairly common, especially at Green Knobs, are fragments of medium- and coarse-grained, foliated or massive amphibolite. Many contain hornblende poikiloblasts, nearly one inch across, in a ground-mass of epidote, green biotite, chlorite, andesine-labradorite, and accessory minerals, including ilmenite with broad leucoxene shells. Cores of large colorless pyroxene crystals were noted in hornblendes of several samples, and plagioclase can also attain considerable size. As a whole, the amphibolites seem to be anamorphosed basic volcanics. Metarhyolites, and similar siliceous igneous rocks, are also representative of the foreign xenoliths.

Among cognate xenoliths, the gabbroic, noritic, and dunitic fragments at Zilditloi Mountain have been mentioned already. It should now be added that both at Green Knobs and Buell Park fragments of peridotites are found. Williams (1936, pp 161, 162) called them lherzolites and harzburgites, which denote peridotite with small amounts of pyroxene, in addition to olivine. These xenoliths are of great significance. They seem to be found in all the South African kimberlite areas, and appear to be characteristic of this rare type of intrusive rocks.

Megascopically, several kinds of peridotite can be distinguished. Some, at Green Knobs, are greenish-gray, rather coarse-grained, massive rocks, so unlike any other fragments that they are immediately recognized as unusual. On the surfaces of many, gray knobs weather in relief, not unlike andalusites in some schists. Another type was seen in relatively small fragments, of greenish or brown color, with slightly pitted, but on the whole smooth, surfaces devoid of more resistant knobs. Broken, both fragments show innumerable short, satiny fibers that crisscross the rock as randomly oriented prisms and plates. Under the microscope, the rocks consist largely of fresh olivine (fa8-10), showing excellent cleavage parallel to (010) with, or without, good parting parallel to (100), and at first sight the minerals suggest pyroxenes (pl 9-C, **D).** The gray knobs are clusters of penninite with magnetite, presumably replacing enstatites. The grains are crossed by antigorite in two or three generations. The oldest are the usual minutely fibrous threads, penetrating the olivine as networks along cracks. They are crossed by slender, straight fibers, 2-3 mm long, and easily recognized megascopically. These fibers are straight, whether they penetrate one or more olivine grains, recalling Gisolf's similar observations (1923, p 193) on peridotites from New Guinea. In places the long antigorites are crossed, in turn, by short-fiber networks of the usual kind. Williams (1936, pp 161, 162) estimates the percentage of olivine and enstatite as 25-70 and 40-20, respectively; however, measurements of the axial angles of many grains showed that more are olivines (2V (—)=84°) than would appear in ordinary thinsection examination, because of the excellent cleavage and parting.

The close genetic relationship between the peridotite xenoliths and the mineral composition of the kimberlite tuff is further illustrated by several large blocks, found at Green Knobs, that contain chromediopside grains of the same size, and with the same optical properties, as the chrome-diopsides in the tuff.

Though these fragments of peridotites have a close analog in South African kimberlite pipes, two other equally significant rocks, eclogite, and phlogopite-peridotite, were looked for in vain. Apparently, they are definitely absent, although it should be realized that an exhaustive search of several square miles of tuff surface may bring to light fragments that may be missed in briefer surveys.

The inclusions have been discussed in some detail because they may be pertinent to a theory that links the two igneous rocks together. It is fortunate that the relationships of a very similar suite of rocks have been discussed by Holmes and Harwood (1932). In the Ruwenzori region, Uganda, kimberlite pipes are associated with olivineleucitite (the shallow-level heteromorph of mica-peridotite). Holmes and Harwood present a number of important arguments to show that kimberlite may be regarded as a peridotitic magma from which, by fractionation, olivine and eclogite have been removed. The sodium-rich pyroxene of eclogite would enrich relatively the residual magma in potash, and would thus be responsible for lavas unusually rich in potash, and sufficiently low in silica that leucite may crystallize. It is for this reason that the dike south of Beelzebub is of great interest. As far as the chemical analyses and the norm (table 15, n 11; table 16) are concerned, this rock is on the boundary between a minette that contains sanidine, and olivine-leucitite. It was called olivine-leucitite by Williams (1936, p 166, analysis 6). Even though the evidence for leucite in this rock is not as conclusive as one might wish, the silicaalumina-potash relations show that this rock belongs to the unusual group of volcanic rocks that are low in silica and high in potash. According to Holmes and Harwood (1932, p 429):

> The igneous or peridotitic type of eclogite has nine times as much Na,O as K2O, and it follows, therefore, that the separation of eclogite and dunite from primary peridotite would fulfill the conditions for producing a magma with the composition required for the generation of mica-peridotites, biotite-pyroxenites, and the lavas of the leucitite series.

To be sure, the rocks of the plugs in these two quadrangles do not fulfill exactly the conditions envisaged by Holmes and Harwood. As yet, no eclogite xenoliths have been found. Mica-peridotite seems to be lacking among the xenoliths, or is so rare that we have not been able to identify it. Minette is more siliceous than leucitite, and olivine is, in our experience, lacking therein. But these negative features do not necessarily invalidate the gist of the Holmes-Harwood theory. Variations in the kinds and amounts of early precipitates, as they clearly recognize, are apt to steer the remaining magma toward contrasting compositions (ibid, p 433); yet the association of two chemically unusual groups of rocks in two separated regions is probably no accident. Holmes and Harwood themselves emphasize that their suggested evolutionary scheme should not be applied too narrowly (ibid, p 432). There is evidence that, under high confining pressure, enstatite may precipitate ahead of olivine (ibid, p 430), and thus the amount of silica left in the remaining liquid may vary, depending on how much olivine or enstatite was removed at depth.

In 1937, Arthur Holmes (1937) published data showing that, according to age determinations by the helium ratio, the cognate eclogite inclusions in the South African kimberlites were much older than the kimberlite. He, therefore, believed that his earlier theory had become untenable, and some years later (Holmes, Arthur, 1950) elaborated other processes that may have influenced the development of potash-rich igneous rocks, low in silica (ibid, pp 783-790). It may be mentioned in passing that the relationship between helium ratio and lead-uranium ratio for the age determination of igneous rocks is still very much under debate (Keevil, 1950; see also Marble, 1952, and Hurley, 1952). To the writers, it seems that Holmes abandoned his valuable theory prematurely, though in some details it may need revision, as is inevitable in this highly speculative field of petrogenesis. Processes of fractionation, taking place at the very lowest levels of the earth's crust, below the most stable shield areas of continents, perhaps proceed at rates very different and much slower than those postulated at shallower crustal levels. This has been strongly advocated for the generation of alkaline magmas by Smyth (1927) and, with proper modifications, may well apply to the formation of the kimberliteminette-trachybasalt association. It seems to the present writers, at any rate, that a process similar to that originally envisaged by Holmes and Harwood may be competent to produce the remarkable association in this area of kimberlite tuff and minette-trachybasalt that approaches in composition olivine-leucitite. Perhaps more detailed investigations in adjacent parts of the Colorado Plateau will provide additional data for deciding to what extent this theory is acceptable.

PLEISTOCENE AND RECENT SERIES

PEDIMENT AND TERRACE GRAVELS

Coarse and fine gravels and sands occur within the area upon pediments and terraces both within Black Creek Valley and Todilto Park, and within and adjacent to Chuska Valley. They occur upon flat-topped ridges and mesas up to 6,900 feet elevation (northwest of Mexican Springs) and as lower surfaces adjacent to most of the drainages within the area. They overlie unconformably the Mesaverde group in the east and the Chinle formation in the west.

The succession of surfaces around Mexican Springs was first described and mapped in detail by Reiche (1941), who differentiated at least eight separate southeast-sloping surface remnants, most of them gravel-capped (fig 20). The more extensive surfaces are believed to be pediment remnants, the lower ones terraces; nearly all are covered by sands and gravels dominantly composed of fluviatile debris from the Chuska sandstone.

A considerable time interval separates the Cretaceous period from the Pliocene (?) epoch of volcanism. Another period of erosion and deposition, later than the volcanic events, is recorded by unconsolidated deposits that are widespread in this region. The oldest of these is a residual soil, here included within the Pediment and Terrace gravels. Somewhat later, on the whole, is a group of stratified silty deposits known as the Nakaibito formation; and still later is the alluvium that forms thin sheets along many gentle slopes of the region, and that occurs, more concentrated, along most stream courses.

The brick-red silty sandstones of the Cutler formation betray their presence even where outcrops are few and weathered. Yet in a large area, south of Sawmill, known to be underlain by these rocks, the surface material is a gray silty soil that supports apparently nothing but sage and a few stunted piñon. Cuts in this material are, unfortunately, lacking, and its nature was obscure until occasional black, gray, and red chert pebbles were found in it that leave no doubt that the silt contains material derived from the Shinarump conglomerate. Its nearest present outcrops are about 2 miles from this silt plain, and on slopes that drain, for the most part, away from the Sawmill plateau. The tops of two isolated hills, 1½ miles east of Piney Hill Lookout, are underlain by upper Cutler sandstone, but, at the very top ledges, loose pebbles of Shinarump chert are abundant, attesting the former presence of this soil cover above the deeply dissected southern margin of the plateau. The nearest outcrops of the Shinarump conglomerate are 8 miles west of these hills.

To explain this distribution of Shinarump pebbles, it must be assumed that a surface of low relief once extended across this plateau, over which debris was washed, derived from outcrops of the conglomerate. Whether most of the pebbles came from the west, north, or east, is unknown; certainly nothing is being added at present. The relief of this plain is so low that only the last endings of the present-day intermittent streams drain it, and most of the blanket of silt and sand is being removed by the slow downhill creep of the soil.

The area tributary to Black Creek affords stronger relief and occasional cuts where the deposits can be seen in cross-section. Narrow forested tracts extend from the periphery of Buell Park toward its interior. They are underlain by lapilli tuff, and nearly all are capped by a reddish sand or gravel, as much as 6 feet thick (fig 15). In addition to debris of Permian sandstones, these gravels contain abundant chert pebbles of the Shinarump formation, both on the east side of the park, where the conglomerate crops out at the rim, and on the west side, where the nearest conglomerate outcrops are much farther away. Although coarser, these deposits are analogous to those south of Sawmill, and record a period of low relief when the bottom of Buell Park stood about 20-30 feet higher than now.

Remnants of pediment gravels are found in many places on the west and east slopes of Black Creek Valley. The largest are shown on Plate 1, and many smaller ones have been seen. One of the largest remnants is an early-cycle alluvial fan, 1½ miles southwest of Zilditloi Mountain. The stream that drains the south slope of this mountain formerly debouched into Black Creek Valley about three-quarters of a mile south of its present mouth and, instead of cutting a canyon, built up a delta, or fan, of considerable size. On its ramplike surface, strewn with abundant basalt debris, one can walk from the axis of Black Creek Valley a long way toward the great Morrison-Dakota (?) scarp, without being blocked by the wall of Entrada sandstone.

Remnants of the pediment veneer, as much as 20 feet thick, are exposed along several intercanyon slopes farther south. They are easily identified where they overlie the white sands of the lower Morrison formation, because the terrace deposits are usually a pale pink, even reddish, as, for instance, in the large "bowl" south of Clay Springs Wash. In several outcrops south and north of that wash, the pediment deposits contain shells of the oysters *Ostrea* or *Exogyra,* derived from Mancos shale that underlies a large area a few miles to the east. Farther

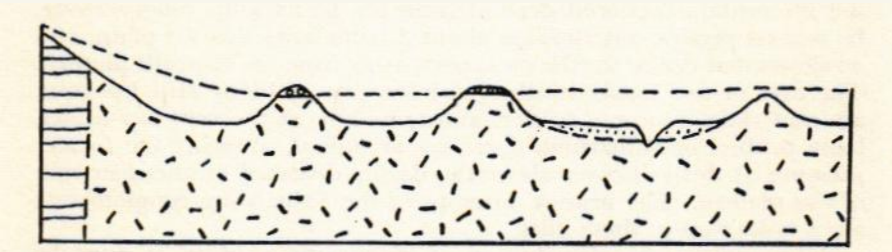


DIAGRAM SHOWING ALLUVIUM OF TWO AGES AT BUELL PARK.

Present intermittent streams flow in steep-walled arroyos, 5-15 feet deep, cutting into stratified alluvium (Nakaibito formation, dots) or lapilli tuff (dashes). Numerous hillocks and low ridges rise 20-30 feet above alluvial plains, underlain by lapilli tuff (right), or capped by 1-3 feet of gravelly older alluvium (to left of center), containing detritus of Cutler and De Chelly formations, and pebbles of Shinarump chert. This blanket has been eroded along the borders of the park, where flat-lying Permian sandstone (horizontal lines near left margin) is cut off by lapilli tuff. Inferred surface of latest Pliocene (?) mature relief shown by dashed line.

Figure 15

north, the topmost 2-5 feet of these deposits contain abundant minette or trachybasalt pebbles, derived from Zilditloi Mountain or the several plugs near it.

Through unusual circumstances the former surface of mature relief in this region can be traced through the southeastern portion of the Defiance Plateau. The kimberlite tuff plug of Buell Park has been mentioned above. No tuff is preserved outside the rim of the park, but as far as 4 miles west of it, and at least 9 miles south of it, single crystals of olivine, pyrope garnet, chrome-diopside, and some actinolite and enstatite are found on anthills (fig 2). Presumably, the tuff, including these minerals, was scattered over a wide area at an elevation several hundred feet above the present land surface. During the subsequent erosion, the tuff itself, as an ash blanket, has been completely removed. However, these resistant minerals must have survived in the residual soil, outlining the minimum area over which the unusual ash was spread. None were found north and northeast of the park, where the dissection by streams has presumably stripped a thicker blanket of residual soil and rocks than in the southwestern part of the plateau. Anthills on the ancient land surface invariably contain more of the igneous minerals than anthills in alluvium; in other words, the redistribution of the residual soil grains in the now active stream systems has so dispersed these grains that they are virtually lost.

One other feature may be briefly touched upon, since it illustrates an obscure chapter of chemical circulation and precipitation in this ancient soil. Navajos, as is well known, bathe in steam which they generate by placing hot stones in water. South of Sawmill, where the residual soil covers large areas, the supply of stones for this purpose presents a problem, since only few Navajos own automobiles with which rocks can be moved over greater distances. Several bathhouses on the upland, 4-5 miles northwest of Fort Defiance, are surrounded by heaps of porous white tufa. Their rotten condition makes them obviously a very poor material for the particular purpose, but in this area there is no substitute. After a search of several days, one ledge of this rock was discovered, about three-fourths of a mile north-northwest of the large, compact forest patch which lies 41/2 miles northwest of Fort Defiance, and about 300 feet east of a much used dirt road leading to Sawmill. The rock is composed of innumerable small chips and flakes of brick-red Cutler sandstone, and fewer Shinarump chert pebbles and Chinle silicified wood, embedded in a groundmass of quartz and feldspar grains cemented by calcite. Scattered irregularly through the rock are white concretions, or geodes, of calcite, about 4 inches across, either solid or hollow. Small patches of coarser calcite in radiating fibers surround individual quartz grains, and considerable masses of chalcedonic quartz are scattered through some of the geodes, so that they weather as knobs.

It is believed that this ledge is a remnant of what may have been a more widely distributed tufa deposit with, or without, accompanying siliceous incrustations. No positive evidence was found for the former existence of hot springs, or a center from which this enrichment in carbonate and silica may have sprung. The porous blocks of white tufa are without exception loose; their distribution suggests that there were several lenses, each about 100-300 feet across. If the material represents a kind of caliche, it suggests some climatic changes in the region, for no caliche is now forming on the entire upland

Windblown silts occur upon the highest pediment and upon the lower terrace surfaces, masking the gravels at many localities. Silts are widespread northeast of Mexican Springs, where they may be as much as 10 feet thick; in several areas recent wind action has produced blowouts and stretches of sand dunes.

LANDSLIDE DEBRIS

Within two areas landslide debris ranging in age from Pleistocene to Recent mantles wide expanses of underlying rocks. Beneath the steep escarpment of Chuska Mountain, extending from south of Chuska Peak northward and eastward to the corner of the map, the Menefee formation and the Tohatchi formation are masked and covered to a depth up to 100 feet by material composed of blocks of Chuska sandstone sometimes as large as a house, and unsorted angular debris ranging downward in size to clay, derived from both the Chuska and from underlying rocks. This area, which is from 2 to 4 miles wide, is cut by narrow, deep gullies and canyons which expose the underlying rocks. The landslide debris rests in a few places upon the higher pediment surfaces, and the activity which produced the landsliding must have begun in Pleistocene time and continued to a lesser degree down to the present, since numerous peaks and ridges, isolated by later erosion, are capped by debris.

Along the western edge of Tohatchi quadrangle the Gallup sandstone forms a high cliff, and the debris from this cliff has moved down over the Mancos shale slopes for distances of from half a mile to 2 miles. Here again the recent gullies and small canyons only occasionally have cut through the landslide mantle to expose the underlying Mancos shale.

RECENT SERIES

GAMERCO FORMATION

Consolidated sand and silt, grading downward into gravel, appears lying upon bedrock toward the bottom of a few of the deeper recent gullies south and east of Mexican Springs. This older alluvial fill has been named the Gamerco formation (Leopold and Snyder, 1951, p 6) from the type locality north of Gallup.

Within the area it is not a mappable unit, although an outcrop at the type locality of the Nakaibito formation (see below) is figured by Leopold and Snyder (ibid, p 10, fig 6).

The age of the Gamerco, based upon Pueblo I and Pueblo II potsherds found in the unconformably overlying Nakaibito formation, can only be given as post-Pleistocene and pre-Pueblo I.

NARAIBITO FORMATION

Deep unconsolidated alluvial fill in most of the larger valleys within the area has been named the Nakaibito formation (Leopold and Snyder, 1951, p 9) from a type locality 4,000 feet west of U. S. Highway 666 in Mexican Springs (the English translation of Nakaibito) Wash.

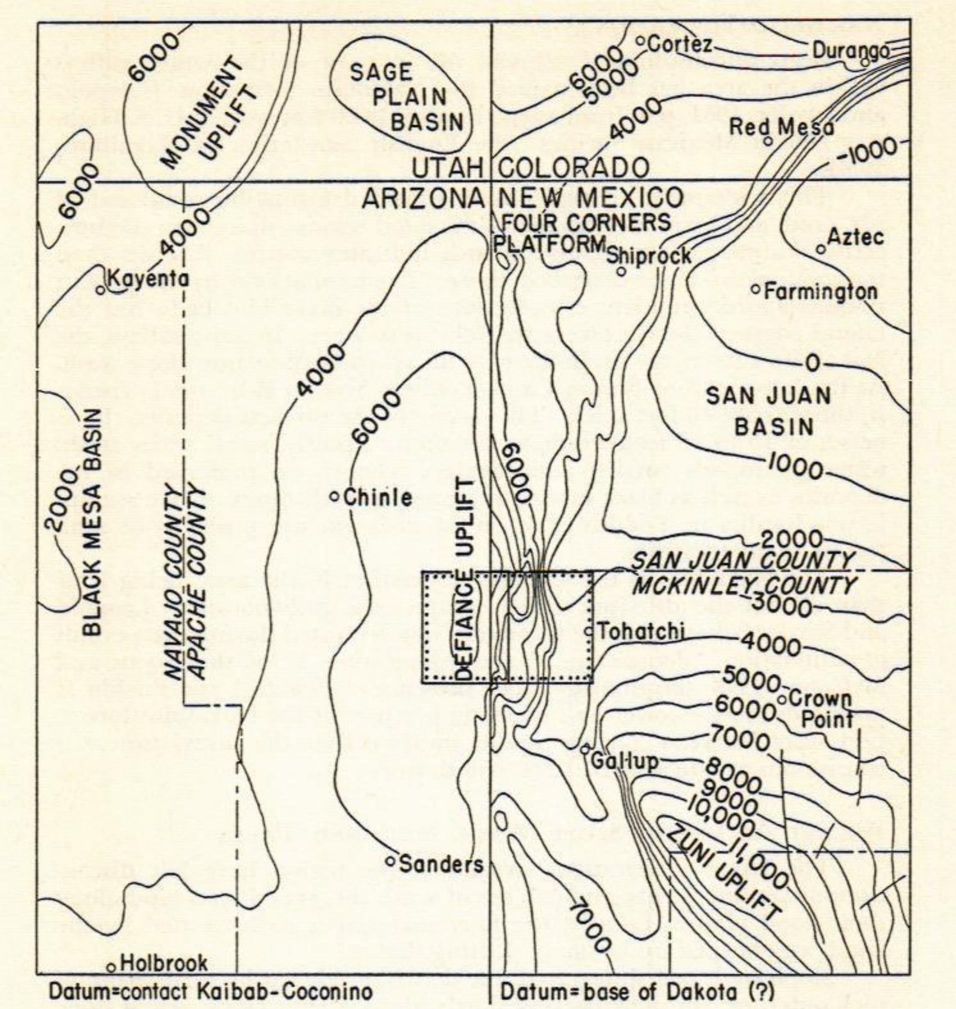
This widespread, conspicuously stratified formation composed of silt, sand, and loam is restricted to the flood plains adjacent to the now active drainage channels, and as such indicates younger deposits than the residual soil cover described above. The trenches cut by the present streams afford abundant cross-sections of the Nakaibito beds, but the lateral edges of the silt layers are difficult to trace. In most valleys, the Nakaibito silts merge probably without sharp borders into slope wash. At the lower end of Bonito Canyon, where Section B-B' (pl 1) crosses it, the silts are 49 feet thick. This is one of the thickest deposits; thicknesses of 15 to 30 feet are more common. Locally, small white freshwater gastropods (snails) and bivalves (clams) are preserved in the deposits, as well as black macerated wood, a small forest of tree stumps in one locality in Todilto Park, and stem fragments, probably of conifers, in many localities.

The Nakaibito is the youngest formation in the area, being later than all but the alluvium which occupies the gully-bottoms. Leopold and Snyder believe that the formation was deposited during two periods of alluviation, "deposition 2" and "deposition 3" of the Bryan and McCann (1943) terminology. The presence of Pueblo I and Pueblo II potsherds "in the lower half of the upper part of the Nakaibito formation near Mexican Springs would indicate that the alluviation was continuous as late as A.D. 1200" (ibid, p 15).

RECENT ALLUVIUM, SLOPE WASH, SOIL, AND TALUS

The larger intermittent streams of the region have left discontinuous veneers, strips, and patches of sand, silt, gravel, and mud along their flood plains. Locally, the finer material is redistributed by the wind, and heaped up in small, shifting dunes.

Slope wash is disintegrated fine debris, produced by weathering of rock outcrops, and moving very slowly along almost every gentle slope of the region, aided by thawing snow, and occasionally speeded up by cloudbursts that soak the soil to a depth of over 1 foot, so that it becomes more mobile for short periods. Especially in areas underlain by shales, slope wash is exceedingly widespread, and merges insensibly with the more or less disintegrated rock at the outcrops. It is impossible, therefore, to draw exact boundaries of this type of alluvium. Similarly, slope wash is apt to accumulate in shallow, poorly drained, local depressions. Owing to their fine-grained, silty composition, these soil patches, though sufficient for grass, rarely support trees. In the Navajo economy, even these small, discontinuous, and widely scattered patches of grassland amidst forested plateaus and slopes are important as grazing areas, or potential soil for cultivation of corn. For this reason, a number of these grassy patches of alluvium have been outlined



STRUCTURAL CONTOUR MAP OF NORTHEASTERN ARIZONA AND NORTHWESTERN NEW MEXICO.

Datum for Colorado and New Mexico is base of Dakota (?) sandstone, with contour interval of 1,000 feet; datum for Utah and Arizona is contact of Kaibab and Coconino, with contour interval of 2,000 feet. After Silver (1950, fig 6), and Hoover (1952, p 11), modified adjacent to map area.

Figure 16

on Plate 1 with dashed or solid lines, but without special letter designations, lest the characteristic color pattern of the photomosaic be obscured.

Talus deposits were mapped at a few places where debris of resistant rocks has accumulated on mountain slopes to such an extent that it obscures the underlying rocks. Zilditloi Mountain is a good example, and nearly all other minette plugs have talus aprons on at least some of their slopes.

STRUCTURE

REGIONAL FEATURES

The boundary area of New Mexico and Arizona covered by this study involves several Colorado Plateau structures which extend north and south far beyond the borders of the map.

These large structural elements appear in a map by Silver (1950, fig 6) and are outlined by Kelley (1951, p 125) as the Defiance uplift (and Defiance "monocline") and San Juan Basin, including the Gallup embayment. They are shown in Figure 16.

The crest of the broad Defiance uplift, an anticlinal warp which extends some 85 miles from a point near U. S. Highway 66 on the south to the northern end of the Lukachukai Mountains on the north, lies along the western part of the map area. This fold dips gently to the west into the Black Mesa structural basin, its eastern flank dipping more steeply into San Juan Basin as the Defiance "monocline."

The area of the map includes a portion of the western edge of San Juan Basin, near the "mouth" of the north-plunging Gallup embayment, where it loses its identity in the central basin owing to the fading out of the northern extension of the Zuni uplift.

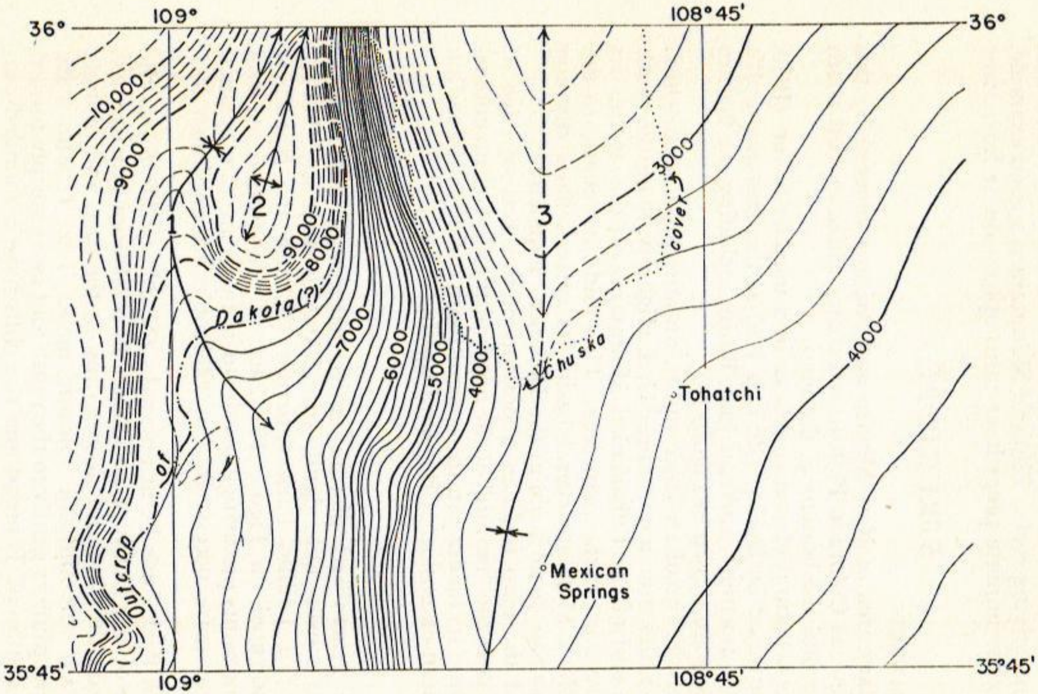
FOLDS

The above generalized picture omits features of lesser extent which may have considerable significance. Among these are the Zilditloi syncline (1), Todilto Park anticline (2), and the Nakaibito syncline (3), indicated on Figure 17. Lack of topographic control within the area prevents picturing these features by means of a detailed structural contour map; necessarily the 200-foot contours shown lack accuracy.

The Todilto Park folds lie at an angle (N. 20° to 30° E.) to the north-south axis of the Defiance anticline. The Zilditloi syncline has very gentle dips on the west and steeper dips on the east, and plunges southward beneath the Zilditloi volcanic mass. The Todilto Park anticline, or dome, plunges gently to the south and more steeply toward the north. The south end is broad and the cliffs have a rounded outline; the north end is abrupt, with an acute angle, the west-dipping flank abruptly changing (with slight fault displacement at the axis) to the steeply dipping east flank.

The asymmetrical Nakaibito syncline trends slightly east of north; dips along the west flank average 14 degrees, steepening to 35 degrees at the north edge of the map. The east flank seldom exhibits dips of more than 3 degrees.

Figure 17



STRUCTURAL CONTOUR MAP OF TOHATCHI QUADRANGLE AND ADJACENT AREAS.

Datum is top of Dakota (?) sandstone. Contour interval 200 feet. Dashed lines west of Dakota (?) outcrop and beneath cover of Chuska sandstone. (1) Zilditloi syncline, (2) Todilto anticline, (3) Nakaibito syncline. Data in eastern part from drillers' logs of water wells (see fig 3 and table 3). Top of Dakota (?) sandstone is about 1,000 feet below top of Dalton sandstone in the northern and 1,100 feet below in the southern part of the area.

The small flexure shown in the southwestern corner of Figure 17 is the northernmost extension of a northwest-trending syncline which includes the area of the Fort Defiance coal mine.

FRACTURES

Fracture systems are well developed in nearly all of the consolidated rocks of the area, and their orientation was measured at several hundred outcrops. Joints, although of great importance because they conduct ground water and other fluids along particular directions in the earth's crust, and influence the weathering of all rocks, are difficult to interpret in mildly deformed areas because stresses of various orientation can produce nearly identical fracture patterns. After larger continuous areas have been surveyed, joints can be interpreted more reliably, but since almost nothing is known about the orientations of fractures in nearby areas, the following brief remarks should be considered as merely one out of many possible interpretations.

Nearly vertical, northeast-striking joints are developed throughout the entire central and southwestern parts of Fort Defiance quadrangle. Innumerable arroyos and short ravines parallel them, and they are observable at once on any airphoto of this region. Their importance for the formation and configuration of cliff fronts and water courses is considerable, but the nature of the stresses that caused them to form will remain obscure until the entire Defiance uplift has been mapped, and the joints have been measured.

As the western border of Fort Defiance quadrangle is followed from south to north, the fractures vary in strike from northeast-southwest through east-west to northwest-southeast. Although in the central area exposures are few and small, and joints may have been overlooked, the prevalence of northwest-striking joints in the northwestern corner of the quadrangle is clearly apparent. In the large, continuous exposures of the ravines that discharge northwestward into Monument Canyon (extreme northwest corner of Fort Defiance quadrangle), innumerable northwest-striking fractures are seen, but virtually none in any other direction.

The varying directions of strike of the joints mapped in Fort Defiance quadrangle converge toward Buell Park. It would be tempting to interpret this as the result of a radial expansion of this district, owing to the volcanic eruptions that centered at the park. But again the answer cannot be definitive until it has been established that the seemingly radiating fractures are not parts of systems that belong to unrelated, independent areas nearby.

The eastern slope of the Defiance uplift is steeper than those on the north and west. Accordingly, the tangential stretch along this zone must also have been somewhat greater than elsewhere. This is borne out by innumerable joints in this entire zone that dip steeply west or northwest, nearly at right angles to the dip of the bedding. No displacements of joint blocks have been noted, and it is assumed that the fractures are, essentially, tension joints. Those that dip west are believed to have formed in response to this stress, whereas the northwest-dipping ones could be interpreted equally well as older, subvertical fractures, tilted during the uplift of the Defiance Plateau.

In this connection, some minor slip zones on the east side of Black Creek Valley should be mentioned. As one walks up any of the large, talus-strewn slopes that lead toward the scarp of the Dakota (?) sandstone, he cannot fail to notice blocks of gray sandstone with snow-white, brilliantly polished slickensides, and strong grooves. It was first thought that they belonged to a major fault zone. However, inspection of many cliffs shows that the Dakota (?) sandstone, almost alone among the several sandstone formations on the east slope of the valley, is crisscrossed by hundreds of irregular slickensides, coated with white, porcellaneous films of aphanitic quartz. Some of these follow bedding planes, others extend, as irregular cracks, like a network through local masses of the sandstone. A few are vertical, and striations on them are in nearly horizontal directions, the east-west slickensides appearing to exceed in number those of other directions. Despite their abundance in the Dakota (?) scarp, the slickensides hardly anywhere allow one to measure the magnitude of displacement along them. Out of several hundred that were seen, only a handful show visible offsets, restricted to a few millimeters, none exceeding 1 foot. However, the striae on nearly all these randomly oriented slickensides trend east-west or nearly so. East of the north-south trending zone of the Dakota (?) scarp, dips are low, commonly horizontal, whereas west of the zone, the strata bend up to the Defiance uplift, and dips up to 20 degrees are seen. It could be assumed, therefore, that the slickensides have acted as planes of adjustment in the hinge zone where nearly horizontal sandstone beds were flexed, and the planes would have served as small-scale slip zones to permit one group of relatively unwieldy sandstone beds to move at a slightly different rate from that of its neighbor beds.

Abundant slickensides also are to be seen in the Todilto limestone along the east side of Todilto Park. Here the limestone is frequently penetrated by numerous thin calcite veinlets, the majority of which, when the rock is broken, show slickensided surfaces.

It was pointed out in the section on igneous rocks, that all the igneous plugs and dikes in this region are located along a broad zone, trending east-west to east-northeast and west-southwest. Fractures of this strike are seen in places, but are not so ubiquitously developed as to attract attention in the field. In the absence of closely spaced fractures in this direction in the sandstone formations, it is tentatively assumed that a broad fracture zone of this direction transects the underlying pre-Permian rocks, and has probably served as an avenue of advance to the kimberlite tuff and minette-trachybasalt sequence.

The funnel fractures near the outer edges of the Buell Park and Green Knobs tuff plugs were mentioned in the section on igneous rocks.

Faulting within the area is rare, apparently being restricted to regions of sharp folding (north end of Todilto Park) and volcanic activity (Buell Park, plugs in south end of Todilto Park).

The fault on the northern axis of the Todilto Park anticline is nearly vertical, with upward or northward displacement of the east side to the extent of several hundred feet, resulting in the stratigraphic displacement of the Todilto limestone of about 50 feet.

Small displacements of the Todilto limestone and the limestone conglomerate at the top of the Chinle formation are exposed in several gullies along the east edge of Todilto Park, and have probably been effective in the localization of the gullies. Displacements (south side down) seldom exceed 10 feet.

Fractures occupied by igneous dikes occur at several localities. A breccia vent in south Todilto Park has a vertical dike extending for 2 miles due east, and west towards Zilditloi. No displacement could be determined on this fracture.

LANDFORMS

GENERAL STATEMENT

The map area lies entirely within the Navajo section of the Colorado Plateau province, and embraces within it the subdivisions of the Defiance Plateau on the west, Black Creek Valley, Chuska Mountain on the north, Manuelito Plateau on the south, and Chuska Valley on the east. These have been defined, after Gregory, by Fenneman (1931, fig 112, p 313) as follows:

1. Defiance Plateau: a domed plateau 6,000 to 7,000 feet high with wide flat valleys trenched by canyons of streams from the Chuska Mountains.
2. Black Creek Valley: chiefly the fiat open valley of Black Creek.
3. Manuelito Plateau: steep-sided flat mesas above 7,000 feet elevation, separated by flat valleys or washes.
4. Chuska Mountains: steep-sided, flat-topped remnants of horizontal sandstone, reaching to 9,000 feet elevation, and in part forested.
5. Chuska Valley: broad scarped plains bearing mesas with wide swales trenched by shallow canyons; lower surface truncating the dipping beds of a shallow syncline, making some cuestas and hogbacks.

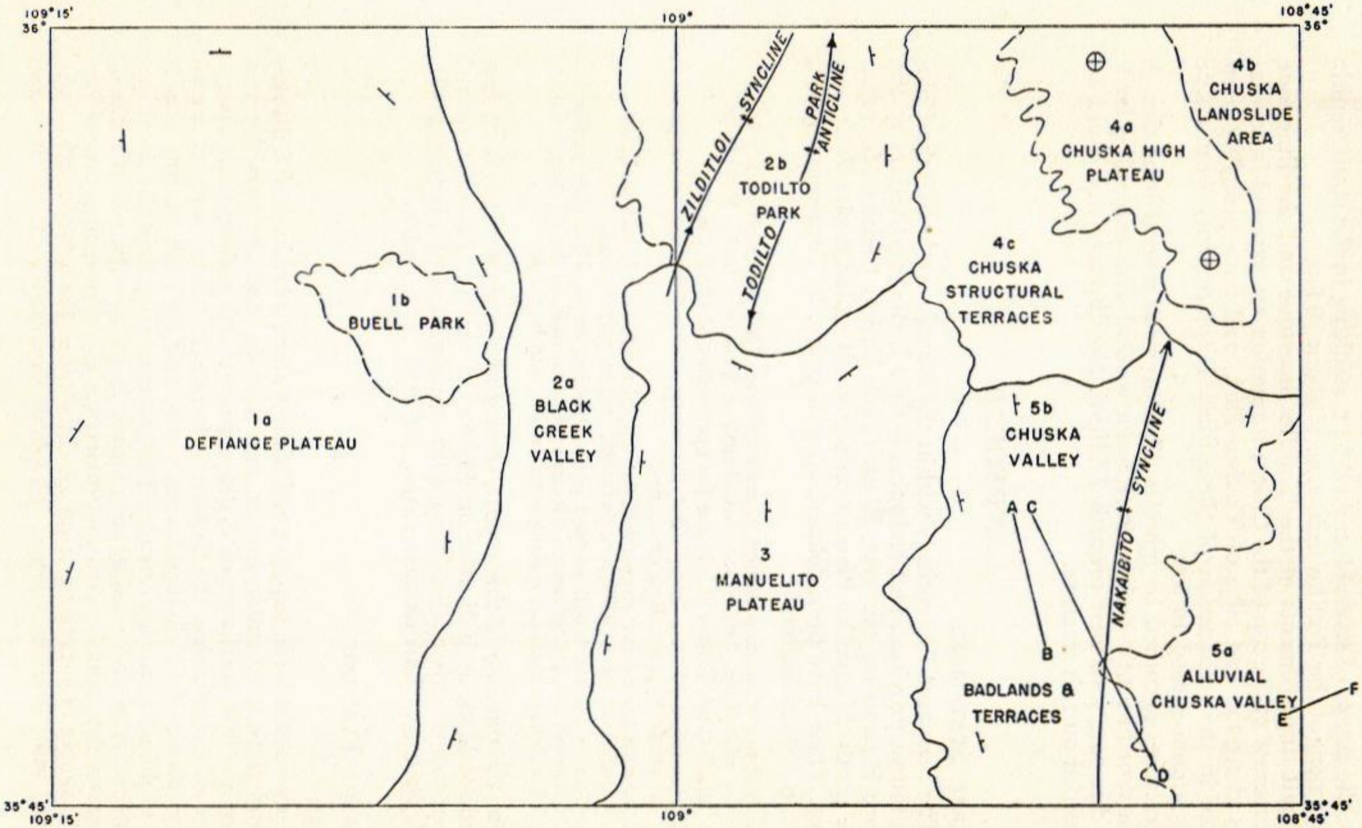
For the purpose of this report, several of the above have been further subdivided, as indicated on Figure 18 and in Table 18 below. Comparison of this outline map with the diagram of Figure 19 will bring out the various characteristics outlined in the table.

DEFIANCE PLATEAU

Plateau

Between the wide expanse of Chinle Valley, with its lavish display of pastel tints of lavender, brown, and maroon, and the grayish-green Cretaceous hills northwest of Gallup, dotted with piñon, there rises a fiat-topped broad ridge, the Defiance Plateau. Its slopes support a continuous forest of virgin ponderosa pines, and its dark outline sets it off from the surrounding terrane. The plateau is, geologically speaking, an uplifted arch, and erosion has reached in its core the oldest rocks of northeastern Arizona, a series of quartzites of unknown, perhaps Precambrian age. Overlapping it on all sides are sedimentary rocks of the Permian and Triassic systems. The beds dip gently off to the west,

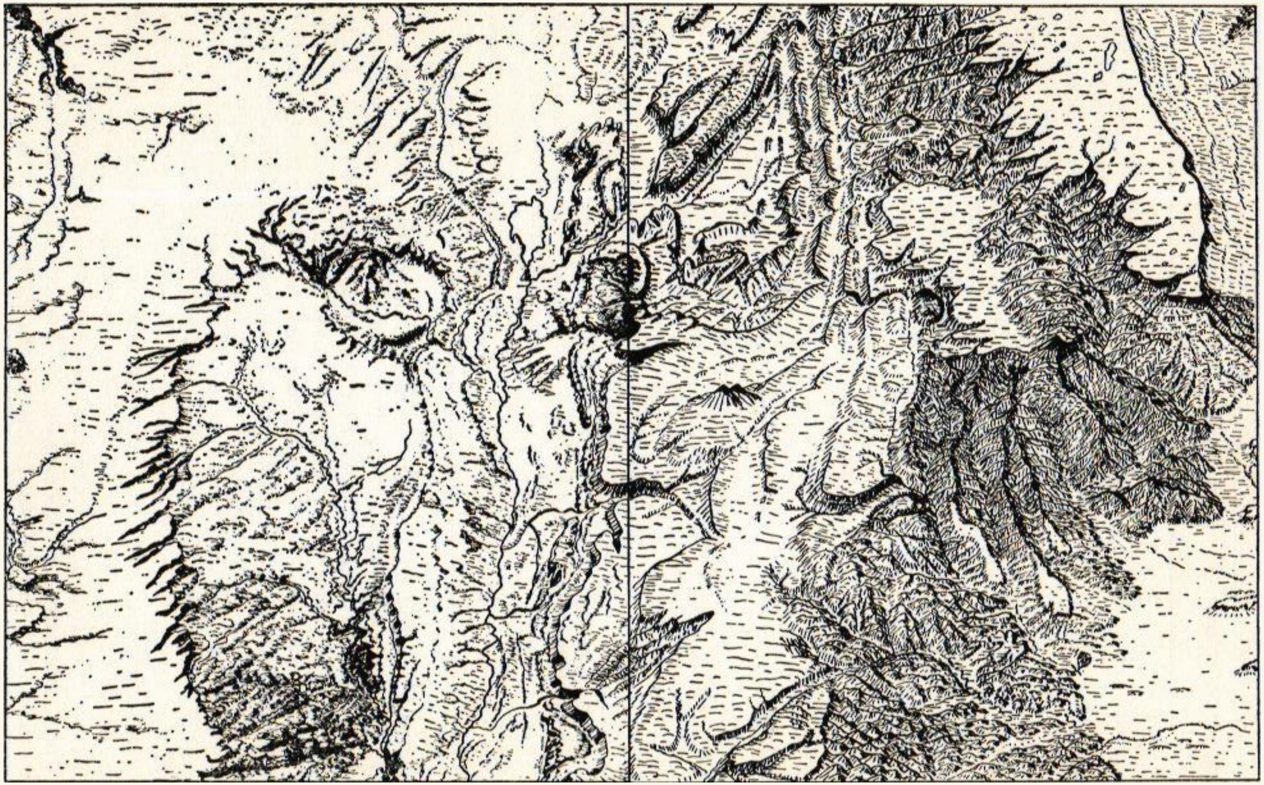
Figure 18



Physiographic divisions and structural pattern of Fort Defiance and Tohatchi quadrangles.

Arrows show direction of plunge of folds; T's show strike and dip of bedded rocks; cross within circle indicates nearly horizontal beds. Section lines A-B to E-F refer to Figure 20.

Figure 19



LANDFORMS SKETCH OF FORT DEFIANCE AND TOHATCHI

Compare with Figure 18.

TABLE 18. PHYSIOGRAPHIC DIVISIONS AND THEIR CHARACTERISTIC FEATURES

PHYSIOGRAPHIC DIVISIONS	ELEVATIONS (in feet)	CHARACTERISTIC FEATURES
1. Defiance Plateau		
a. Plateau	6,800-8,300	Broad, north-south anticline with stripped structural slopes.
b. Buell Park	7,100-7,800	Circular diatreme caldera, with ring and central intrusions.
2. Black Creek Valley		
a. Valley	6,700.7,100	Subsequent, monoclinal valley in Chinle formation.
b. Todilto Park	7,100-7,500	Eroded dome and syncline in massive Jurassic rocks.
3. Manuelito Plateau	7,500-8,200	Structural terrace in Mesaverde group, bordered on west by cuesta, on east by monocline.
4. Chuska Mountain		
a. High plateau	8,500.9,100	Horizontal mesa in Tertiary sandstone.
b. Landslide area	6,400-8,500	Wide strip of landslide splinters and debris around Chuska Mountain.
c. Structural terraces	8,200-8,400	Horizontal erosional bench in Tertiary sandstone.
5. Chuska Valley		
a. Alluvial valley	6,200-6,400	Broad pediment in Menefee formation, lower parts alluviated.
b. Badlands, terraces, and pediments	6,400-8,000	Eroded monocline and syncline in Menefee and Tohatchi formations, with pediment and terrace remnants at many levels.

north, and east, and so uniform is their composition that even the sensitive test of weathering, rain, and wind has discovered but few beds of superior resistance to mark them as cliffs, mesas, or bluffs. Brick-red, or gray, soil covers the innermost group of shaly sandstones, the Cutler formation. But where these rocks pass under the next younger De Chelly sandstone, a prominent cuesta develops, facing inward, and reaching elevations of nearly 8,000 feet on the west slope, almost 500 feet above the level of the innermost plateau. An ancient residual soil covers much of this, but none has been found on the De Chelly plateau. Instead, the flat surface follows essentially the bedding planes of this tan or pale-brick sandstone, and countless low outcrops dot the ground between the tall pines. The De Chelly plateau is wide on the west flank, but narrows northward. On the east, where the slope is steeper, the succeeding Shinarump conglomerate, of Triassic age, covers the De Chelly sandstone a short distance east of the eastern cuesta.

The resistant surface of the Shinarump conglomerate sustains a flat, spurlike extension of the plateau that reaches the southernmost endings of the great De Chelly Canyon system seven miles northwest of Sawmill. From this point a gentle slope leads westward to Chinle Valley, and a flat prong extends north and northeast, gradually sinking to the level of the Chinle shale belt that fringes the Defiance uplift on the north and east.

Buell Park

The morphological simplicity of this uplifted block is interrupted in two places. At Buell Park, 21/2 miles east of Sawmill, the Permian sandstone plate has been pierced by a volcanic explosion that drilled a vertical channel, 2 miles wide, through the plateau, and that must have showered the vicinity with ashes, lapilli, and lava. Possibly, an active volcano, with short lava flows extending from the central orifice, stood in Pliocene time above the park. However, the subsequent erosion has removed this entirely, and at present the pipe is a depressed circular area, rimmed with steep cliffs, in which the Cutler, De Chelly, and, in places, the Shinarump, are magnificently exposed. Some of the more resistant volcanic rocks form Buell Mountain, that rises above the level of the surrounding De Chelly sandstone plateau, but the bottom of the park is a gently undulating surface, revealing the green kimberlitic tuff under a discontinuous blanket of an old residual gravel, into which the tributaries of the present streams have etched narrow, but steep-walled, ravines.

Buell Park has counterpart in Fluted Rock, a massive block of lava rising 400 feet above the De Chelly plateau. It, too, is a volcanic plug, but of uniformly resistant material. Its flat summit, 8,308 feet in elevation, is the highest point on the Defiance Plateau.

BLACK CREEK VALLEY

Valley

This valley drains the east flank of the Defiance Plateau and the southwestern slopes of Chuska Mountain. Like its western counterpart, Chinle Valley, it is carved in soft but colorful Chinle shales with intercalated sandstone lenses. The shales and clays make flat, grassy plains between low cuestas and hills supported by sporadic harder beds, giving the valley an average width of 2 miles.

The west slope of the valley is, essentially, the dip slope of the Shinarump conglomerate or, in the northern area, the dip slope of a group of thick sandstone and conglomerate lenses in the lower Chinle formation. South of Todilto Park, the east slope is the series of Jurassic sandstone cliffs that build up a succession of parallel, west-facing hogbacks, or cuestas, below the cliff of the Dakota (?) sandstone. At the south end of the park, the valley divides, and the northern continuation of the meridionally trending Black Creek Valley is a flat and featureless depression, the east flank of which gradually rises to the level of a group of limestone-pellet conglomerates that form a subdued plateau, about 200 feet above the valley.

In latest Pliocene or Pleistocene time, Black Creek must have flowed in a much flatter valley. Its slopes can be reconstructed fairly accurately from remnants of gravels and sand, especially on the east side. They suggest that the crests of the highest cuestas were about flush with an apron of unconsolidated deposits that formed a smooth, more or less continuous slope from the Dakota (?) sandstone cuesta to the axis of the valley. This slope was about 30-150 feet higher than corresponding sections of the present slope, and debris from the Man-cos shale has been transported thereon across the Morrison and Summerville-Entrada cuestas. Remnants of this high-level veneer of gravel are found also on the northwest flank of Todilto Park and on the west slopes of Black Creek Valley.

Todilto Park

Probably the most spectacular and scenic part of the entire area is Todilto Park. Here 20 miles of 200-foot, vertical, red cliffs, accentuated by great overhanging arches and narrow spires (see pl 2, Frontispiece), bound several thousand acres of wide, nearly flat, grassy plains and low-rolling hills. The name "Todilto," meaning "breaking out of the waters," is said to have originated in the legend that the park was once occupied by a great lake, which broke out and drained itself in a day. This legend may have some basis in geologic fact!

This magnificent amphitheatre is the result of erosion by streams which head in Chuska Mountain to the east and drain into Black Creek. Two geologic structures, an anticline and a syncline, arch the massive red Entrada and Summerville sandstones, so that the underlying soft and easily-worn-away Chinle shales could be cut out, sapping and undermining the cliff-making sandstones to produce the long escarpments. The gentle slopes at the foot of the cliffs are underlain generally by the Wingate sandstone, and long, low ridges in the park are held up by thin resistant layers of limestone and sandstone in the Chinle formation.

At least two erosional surfaces occur in Todilto Park, the upper being capped by terrace gravels, the lower representing the widespread surface of the Nakaibito alluvial or lake fill. Level areas between these two surfaces probably represent intermediate stages of lateral erosion during downcutting. Within the last 100 years erosion has cut steep-walled arroyos, from a few feet to 50 feet in depth, into the Nakaibito fill, in some cases exposing older underlying rocks in their walls. In one case it has exhumed a small forest of stumps buried thousands of years ago when the fill first began to accumulate, or lake was formed.

MANUELITO PLATEAU

The Manuelito Plateau in this area is a northern extension of the subdivision as mapped by Gregory (1917, pl I). Like the plateau to the south, it consists of flat-lying and truncated east-dipping beds of Cretaceous age, and is bounded on the west by the escarpment of the Defiance monocline. Northward it terminates in the south- and east-dipping cuesta of the Todilto Park anticline, and to the east the Mesaverde rocks steepen to form a monoclinal escarpment, in part composed of dip-slopes of the more resistant beds, in part of dissected badlands and sandstone cuestas. The summit surface is partly a structural terrace of resistant sandstone beds, partly a stripped peneplain, once capped unconformably by the Tertiary Chuska sandstone, which, northeast of the plateau, remains to form the main mass of Chuska Mountain. Near the center of the map area an isolated outlier or remnant known as Twin Buttes rises to an elevation of 8,546 feet, nearly 600 feet above the plateau surface. The surface of the plateau consists of low, rolling hills and long, low ridges with a relief of seldom over 50 feet. Narrow canyons from the east and west dissect the edges of the plateau.

CHUSKA MOUNTAIN

The southern end of Chuska Mountain occupies the northeastern part of the mapped area. This high, relatively flat-topped plateau is underlain by 700 to 1,100 feet of Tertiary Chuska sandstone which rests unconformably at about 8,000 feet elevation upon evenly bevelled, east-dipping beds of Jurassic and Cretaceous age. Within the area, the plateau surface is from 2 to 4 miles wide at about 9,000 feet elevation; lower terraces, eroded ridges, and landslide blocks extend several miles to the east and west.

High Plateau Subdivision

The Chuska Plateau is a gently undulating surface with low, generally rounded hills of sandstone not over 100 feet high, alternating with wide, alluvium-filled, and generally closed depressions, frequently occupied by small lakes and ponds, which in a few cases are as much as 1 mile in length. Nearly 130 such lakes and ponds can be counted on the large-scale aerial photographs (1933). The western edge of this surface is dissected by steep-walled canyons, the heads of which may occupy a narrow gorge, extending for as much as 1 mile into the plateau surface, and drain a considerable area. In contrast, the eastern edge of the plateau is a relatively straight, generally cliffed escarpment which abruptly transects all surface features.

Landslide Area Subdivision

Below the upper line of cliffs of Chuska sandstone and their talus slopes on the east side of the plateau, a series of from 2 to 5 more or less parallel ridges, from a few hundred feet to as much as 2 miles in length, occurs at successively lower elevations eastward. The depressions between the ridges, which are commonly closed, have been covered in part or wholly by silt and alluvium. These ridges and adjacent depressions have been explained as being formed, (1) by progressive splitting off and slumping of narrow splinters of Chuska sandstone from the cliffs above, which rode down the underlying slopes of highly bentonitic shales, and (2) by successive accumulation of talus material during the pluvial stages of the Pleistocene, when deep snowbanks formed on the eastern lee slopes of the plateau; this material falling from the cliffs, and sliding down the surface of the snowbanks and lodging at their base (Reiche, personal communication).

Below the ridged area, the surface breaks off into regions of typical hummocky landslide topography which in some places, as northwest of

Tohatchi, extends all the way down to the valley level, and in other places, as 3 miles north of Tohatchi, has been stripped off by erosion which has produced badlands in the underlying Cretaceous shales.

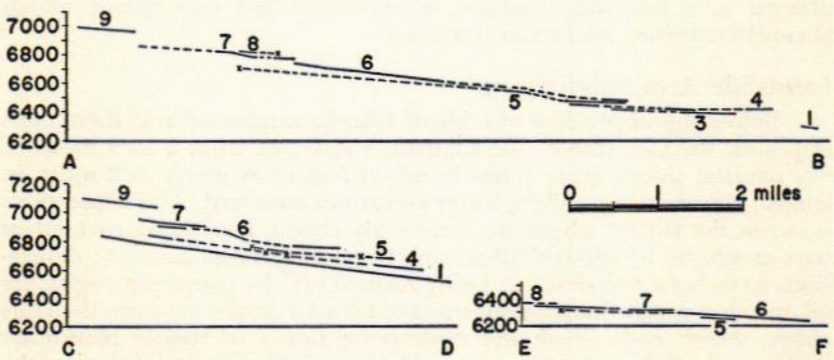
Structural Terraces Subdivision

West of Chuska Plateau, at an altitude around 8,300 feet, a wide, almost flat surface covering nearly 5 square miles has been developed upon a resistant sandstone layer about 200 feet above the base of the Chuska sandstone. This structural terrace extends from a point northwest of Chuska Peak 4 miles along the west side of Chuska Plateau, and is 1-2 miles wide. At the north end it is dissected by the youthful tributaries of Todilto Wash. Several outlying remnants occur farther north on ridges between these tributaries.

CHUSKA VALLEY

Chuska Valley occupies approximately the southeast quarter of Tohatchi quadrangle. The southeastern one-third of this area, comprising the alluviated valley subdivision, is nearly flat, with only occasional flat-topped mesas and low hills interrupting the alluviated plains. The rest of the area, here called the badlands and terraces subdivision, is dissected, and has relief varying from a few tens of feet to as much as 1,000 feet.

The landforms within the two regions referred to above have been largely sculptured during the late Pleistocene and Recent epochs. During these epochs several cycles of lateral planation and deposition more than once have reduced the area to near maturity, producing several east-sloping terrace and pediment surfaces, commonly capped with coarse gravels, which have been described by Reiche (1941) as being



COMPOSITE PROFILES OF STRIPS, A QUARTER OF A MILE WIDE, SHOWING RELATIONS OF SURFACE REMNANTS AROUND MEXICAN SPRINGS.

Dashed lines give correlations; x shows small remnant. For location of profiles, see Figure 18. (After Reiche, 1941, pp 62-63.)

Figure 20

divisible into 9 graded surfaces (see fig 20). Numbers 6 and 7 are best preserved and form the prominent flat top of the ridge north of Mexican Springs and the next north-south ridge to the west; similar surfaces cap the mesas along the east edge of the area. The lower surfaces represent successively lower strath developments along the drainage of Catron, Mexican Springs, and Norcross Washes, which originally coalesced to form pediments progressively farther to the east, but are now represented only by numerous isolated remnants.

Alluvial Valley Subdivision

The lowest widespread surface of alluvium is underlain by silty sediments 22 feet thick at the type locality, where it was named the Nakaibito formation by Leopold and Snyder (1951) for exposures in Mexican Springs Wash, 4,000 feet west of U.S. Highway 666. Recent gullying has cut channels up to 25 feet deep in this and older alluvial fills which occupy nearly all the larger washes.

Badlands Subdivision

Headward erosion northwestward into the east-dipping monoclinal sediments of the Mesaverde group in Manuelito Plateau and beneath Chuska Mountain, has produced a deeply incised badlands topography which borders the more subdued regions farther downstream. Some of the canyons cut in Menefee sandstones north of Tohatchi have almost vertical walls up to 100 feet high along the course of the incised meanders.

AGE OF THE SURFACES

The highest graded surface below the Chuska Plateau surface and the Chuska structural terrace is represented by much of the rolling summit of Manuelito Plateau, and possibly by local wide-valley remnants at the headwaters of Mexican Springs Wash and the south branch of Todilto Wash.

The Manuelito Plateau surface represents nearly complete stripping of the Chuska sandstone, and erosion of 50 to 100 feet into the underlying rocks. If the Chuska unconformity represents the "plateau cycle" of Davis (1901, 1903), and the "Zuni erosion surface" of McCann (1938), this surface, upon which is found garnet and peridot derived from the Buell Park or Green Knobs volcanic vents, may be correlated with Robinson's (1910) "new erosion cycle" surface of early Pleistocene age at Grand Canyon. As Reiche points out (1941, p 64), this cycle was rejuvenated and in places covered by landslide debris from Chuska Plateau by a more humid period, undoubtedly connected with one of the pluvial epochs of the Pleistocene, and the succeeding lower terrace and pediment surfaces become stages of the later Pleistocene "Canyon" erosion cycle, as defined at Grand Canyon.

OUTLINE OF PHYSIOGRAPHIC HISTORY

EVENTS	DATE
1. Folding of pre-Tertiary sediments and uplift.	Laramide (U.K. - L. T.)
2. Erosion to old age "Zuni-erosion surface."	Miocene
3. Subsidence (?) or uplift of adjacent area (?), and deposition of Chuska sandstone. First volcanic epoch.	Pliocene ?
4. Uplift and erosion of much of Chuska sandstone, stripping of fossil surface.	Pliocene ? Late
5. Second volcanic epoch (?).	Pliocene ?
6. Superposition of main streams, and headward erosion of chief tributaries, to stage of maturity (highest terraces and pediments).	Upper Pliocene or Lower Pleistocene
7. Main landslides and nivation on Chuska Plateau.	Pleistocene
8. Repeated uplift or rejuvenation, forming lower terraces and pediments.	Upper Pleistocene
9. Alluviation of Gamerco formation.	Uppermost Pleistocene or Recent
10. Erosion and deposition of Nakaibito formation.	Recent
11. Erosion of present arroyos and some redeposition.	Last 100 years

Special Reports

PETROLOGY OF SEDIMENTARY ROCKS

by Max E. Willard

GENERAL STATEMENT

In view of the considerable thickness of elastic sedimentary rocks exposed in the Fort Defiance-Tohatchi area, which provides a representative section for the southwestern part of San Juan Basin, a laboratory study utilizing the modern techniques of sedimentary petrology seemed particularly fitting as a part of this investigation. It was the hope that such a study would resolve small differences in these rocks, which are almost wholly sandstones and siltstones, in such a way that these differences could be recognized elsewhere, particularly in oil well tests, and the various formations correlated properly. Accordingly, surface samples were taken along measured sections from the top of the Chinle through the Satan tongue of Mancos shale. For samples of formations from the top of the Chinle downward to the Precambrian (?) quartzite, the writer relied on cuttings from Navajo well No. 1 of Humble Oil and Refining Company in Todilto Park which were very kindly supplied by Mr. W. B. Hoover of that organization. The samples on which this investigation is based thus represent a single section.

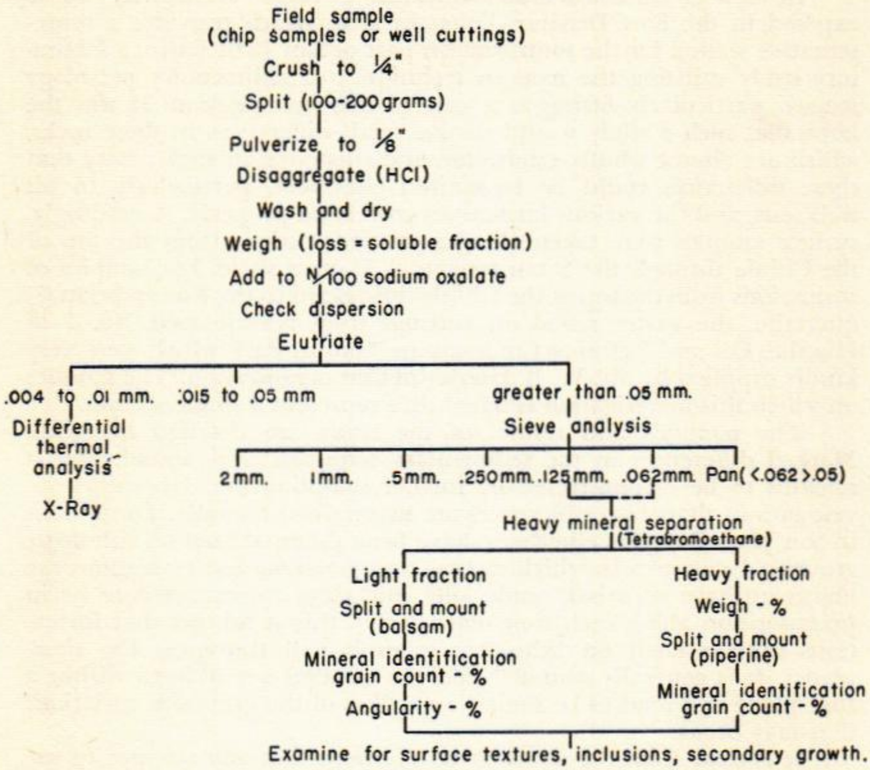
The methods and results of the study are detailed herewith. Marked differences in the sedimentary sequence were found, and it remains to be demonstrated by further sampling and laboratory investigations that these differences are maintained laterally. Formations in San Juan Basin, as elsewhere, have *been* differentiated on lithologic grounds. In an area in which marine transgressions and regressions are known to have occurred, sands, silts, and clays are expected to be in juxtaposition along each time-plane. From this it follows that formations differentiated on lithologic grounds will transgress the time-planes. It is generally assumed that the mineral assemblages within a time-plane will tend to be similar regardless of the grain-size variations that may occur.

It is clear from the above generalizations that any attempt to use the data in the following sections of this report as a basis for correlating mapped formations should be made with caution. Careful comparison of these findings with similar data from other stratigraphic sections in San Juan Basin may, however, result in a more complete understanding of the geologic history of this part of New Mexico.

SAMPLING AND LABORATORY OPERATION

The methods of sampling and the principal laboratory operations are outlined in Figure 21 (in Pocket).

Chip samples regularly spaced across the exposed beds in strati-graphic Section 1 (see pl 11) were collected by Wayne Bundy. This stratigraphic section was measured by Allen and Schilling, and includes the formations from the Westwater Canyon sandstone member through the lower part of the Satan tongue of Mancos shale. Sampling below the Westwater Canyon sandstone member to the upper part of the Chinle formation was done by Allen and Bundy along a measured section (pl 11, Sec 4) in Todilto Park. All the samples from the lower Chinle formation to the Precambrian (?) came from Humble Oil Company's Navajo well No. 1, in the line of Section 4, as represented by cuttings generously supplied by Mr. Hoover. Composite samples were



LABORATORY OPERATIONS FOR SEDIMENTARY PETROLOGY.

Figure 21

made from each of the lithologic units that were megascopically obvious in the well cuttings. Correlation between these lithologic units and exposed formations was made on the basis of megascopic similarities, hence subsequent studies may require some revision of these correlations. The formation names used correspond to those employed in the main text.

Preparation and disaggregation of the samples were done in the standard manner. Crushing and pulverizing were adjusted to avoid breaking of individual mineral grains.

Elutriation was chosen as the means of separating the finer-grained fractions, because it produced a concentration of those fractions large enough for subsequent differential thermal analysis and X-ray examination. The apparatus used is a two-vessel, rising-current elutriator.

The size fraction of each sample containing grains greater than .05 mm in diameter was mechanically analyzed. Whenever possible heavy minerals were separated from the size fraction between .250 mm and .125 mm. In several of the samples the percent of heavy minerals within this range was inadequate and in these the size fraction between .125 mm and .062 mm was used.

Angularity of individual grains was determined by Fisher's method of computation, as described by Krumbein and Pettijohn (1938, p 289). The computations were applied to between 20 and 30 grains of a mounted sample of the light minerals. The method is probably not sufficiently accurate to demonstrate minor differences in angularity, but it reveals adequately the larger, more significant changes.

A portable apparatus was used to obtain the differential thermal curves in Plate 13 (in Pocket). The heating curve for this apparatus flattens abruptly between 750° and 800°C; hence only the strongest thermal reactions above those temperatures are recorded. Many of the clay-size samples were analyzed two or more times; the results demonstrate that curves obtained with this portable apparatus are reproducible. The thermal curves in Plate 13 are not closely comparable with curves obtained with more elaborate equipment, but the similarities are sufficient to permit tentative identification of many of the clay minerals.

Several of the clay-size samples were examined with the electron microscope, and with X-ray.

SUMMARY OF RESULTS

Percent Soluble

The percent of soluble material was determined during disaggregation of the samples by means of dilute hydrochloric acid solutions. The soluble portions of the samples were largely calcium carbonate; a small amount of iron was also removed.

The results of the solubility determinations are summarized in Plate 14, Column C (in Pocket). The amounts of soluble material in the sedimentary units between the Summerville formation and the Dilco member of the Crevasse Canyon formation are remarkably low; in only a few do they exceed 5 percent.

High solubility occurs at the top and near the bottom of the stratigraphic section. Sample 2 from the Cutler formation is more than 30 percent soluble and Sample 42 from the Satan tongue of Mancos shale is more than 40 percent soluble. Both these samples are very fine sandstone and siltstone.

Sieve Analyses

Data from the sieve analyses and the elutriation have been combined in cumulative curves. These curves are not included in the report, but may be examined at the New Mexico Bureau of Mines and Mineral Resources, in Socorro.

Results of the size analyses are summarized in Plate 14, Columns E and F. The range in medium sizes is between medium sand and silt. No shales or coarse sediments were found in the sampled sections, though coarse sediments appear elsewhere in the Fort DefianceTohatchi area. The Shinarump is pebble conglomerate in places, very coarse sandstone and conglomerate also being observed in the West-water Canyon and Gallup sandstones.

All the samples are either moderately or well sorted. Between Sample 16 from the Wingate sandstone and Sample 42 from the Satan tongue of Mancos shale the coefficient of sorting ranges between 1.1 to 2.0. Sediments having a sorting coefficient less than 2.5 are considered well sorted.

A marked change in the degree of sorting occurs at the top of the Chinle formation; the coefficient of sorting for Samples 14 and 15 is 3.0 and 3.3. The cumulative curves for these and the remaining samples of the Chinle formation are not smooth. In fact, each of these curves appears roughly divisible into two parts on the basis of the irregularities. This division suggests that the sediments making up the samples are of two genetic types, of which one owes its origin to volcanic activity.

Heavy Minerals

The percentages by weight of heavy minerals in the samples are shown in Plate 14, Column A. In some of the samples the .125-mm and .062-mm size fractions were inadequate for heavy-mineral determinations, and in others these size fractions were largely composed of rock fragments. In the Chinle formation the latter condition was common, hence these samples have been labeled undeterminable in the summary chart.

The percentage of heavy minerals is conspicuously low in the Summerville formation, Westwater Canyon sandstone member, Dakota (?) sandstone, and Mancos shale. Above and below this part of the section a marked increase in the amount of heavy minerals was observed. Samples from the Chinle formation, Gallup sandstone, Point Lookout sandstone, and the Satan tongue of Mancos shale contain approximately one percent heavy minerals. The amount of heavy minerals in the Entrada sandstone is also striking, because of the much lower percentages in the rocks above and below.

Qualitative and frequency relations between heavy-mineral suites and stratigraphy are presented in Plates 15 and 16 (in Pocket). Biotite, chlorite, augite (?), titanite, and zoisite for the most part are confined to formations above the Mancos shale. Similarly muscovite is most abundant in the upper part of the sampled section. In the Satan tongue of Mancos shale titanite is present as angular fragments and as well-developed euhedra, which suggests that it may be in part authigenic.

Tourmaline. Tourmaline is present in all samples except Sample 17 from the Carmel member of the Entrada sandstone and Sample 37 from the Dalton sandstone tongue. The absence of tourmaline in these samples may prove to be of value in correlation studies.

In most of the samples tourmaline occurs in angular fragments and rounded, highly polished, beadlike grains. The proportions of these two types changes from sample to sample. In general the angular grains predominate in samples from the Mancos shale and overlying formations. Similarly, elongated, prismatic tourmaline grains are most abundant above the Mancos shale.

Both magnesian (brown-black) and alkalic (blue-green) tourmaline were observed in the Wingate sandstone, Entrada formation, Summerville formation, Westwater Canyon sandstone member, and Dakota (?) sandstone. Above and below this part of the stratigraphic section these tourmaline types are not uniformly present.

Garnet. Garnet is absent in Sample 23 from the Westwater Canyon sandstone member, Sample 6 from the Dakota (?) sandstone, and Sample 22 from the Point Lookout sandstone. Garnet makes up 20-50 percent of the heavy-mineral suites from the Entrada sandstone, Summerville formation, and Dilco member of the Crevasse Canyon formation. Euhedral garnet was observed only in Sample 15 from the Chinle formation.

Much of the garnet in the sampled section occurs as angular fragments, but below the Summerville formation both angular and rounded garnets were observed. Most of the garnet below the Summerville formation contains anisotropic inclusions, possibly mica and zircon. Many of these garnets show strain shadows between crossed nicols.

The garnets observed range from colorless, through bluish pink, to reddish brown. Identification of the specific members of the garnet group present might aid materially in differentiating these strata.

Garnets in the Jurassic formations are etched; rectangular and triangular pits and facets are well developed. Similar etch patterns were observed also at two other places in the stratigraphic section, one at the top of the Gallup sandstone and one near the base of the Dakota (?) sandstone.

Zircon. Zircon was not observed in Samples 27 and 29 from the Dakota (?) sandstone, in Sample 30 from the Mancos shale, nor in Sample 38 from the Crevasse Canyon formation; it is present in all other samples.

In Sample 28 from the Dakota (?) sandstone, Sample 34 from the Gallup sandstone, and Sample 37 from the Crevasse Canyon formation, the zircon is attached to quartz grains. Other heavy minerals in these samples were similarly attached.

Both colorless and yellowish-brown zircons are present; the colorless variety is by far the more common. Zoned euhedral zircon was observed in one sample from the Gallup sandstone and in one from the top of the Mancos shale. Zoned zircon is abundant in three of the five samples from the Westwater Canyon sandstone and may be characteristic of that formation.

Staurolite. Staurolite occurs near the top of the Mancos shale and at the base of the Dakota (?) sandstone, but it is most abundant in, and may be characteristic of, the Westwater Canyon sandstone member. Much of the staurolite occurs as yellow or golden-brown cleavage fragments. A few of the staurolite grains have sharply angular "concertina" boundaries. The appearance of staurolite in the Westwater Canyon sandstone is accompanied in the light-mineral fraction by an increase in the percent of feldspar (pl 14, col B).

Iron Ores. Magnetite and ilmenite occur in many of the samples, but are most abundant in the Westwater Canyon sandstone member, and in the Carmel member and Chinle formations. Below the West-water Canyon sandstone member most of the grains are well rounded.

Pyrite occurs in the Mancos shale, Dakota (?) sandstone, and Carmel member. Flakes and irregular masses of iron sulfide, probably marcasite, were observed associated with coaly material in the Chinle formation. Pseudomorphs of hematite after pyrite were found in Sample 3 from the Westwater Canyon sandstone member.

Leucoxene. Irregular grains of leucoxene were found in each of the sampled formations. Pseudomorphs of leucoxene after ilmenite were observed in Samples 28 and 29 from the Dakota (?) sandstone. Several of the pseudomorphs in Sample 28 contained cores of ilmenite.

Epidote. Epidote was identified in only three samples, one from the Mancos shale, one from the Carmel member, and one from the top of the Chinle formation. The heavy-mineral suite from the Chinle formation was 23 percent epidote. Only one or two grains of epidote were present in the other two samples.

Apatite. One grain of apatite was identified in Sample 25 from the base of the Dakota (?) sandstone.

Barite. Barite was identified in surface Sample 22 from the West-water Canyon sandstone member. It occurs as angular cleavage fragments and makes up approximately 10 percent of the heavy-mineral suite. Barite in the well samples is probably not significant.

Sphalerite. Between one and two percent of dark-brown and green sphalerite was observed in the Carmel member as irregular grains and cleavage fragments.

Miscellaneous Heavy Minerals. Mineral grains that were not positively identified occur in several of the samples and are recorded in Plate 16. Rutile, corundum, and augite may be present above the Dakota (?) sandstone. Grains tentatively identified as rutile occur in the Chinle formation, Wingate sandstone, and Carmel member.

Light Minerals

The light-mineral suites from the sampled section consist largely of quartz, potash feldspar, and muscovite. Brown and gray chert fragments were present in samples from the Westwater Canyon sandstone member. Sample 38 from the Crevasse Canyon formation contained angular fragments of gray quartzite similar in appearance to the Precambrian quartzite exposed in Bonito Canyon, northwest of Fort Defiance.

Muscovite. Muscovite is present in small amounts in samples taken between the base of the Westwater Canyon sandstone member and the top of the Mancos shale. A marked increase in the amount of muscovite was observed above the Mancos shale.

Feldspar. A corresponding increase in the percent of potash feldspar also occurs above the Mancos shale (pl 14, col B). In light-mineral suites from the Dakota (?) sandstone and the upper part of the West-water Canyon sandstone member, feldspar is present in only small amounts, never exceeding 5 percent. Feldspar is abundant in the light-mineral assemblages from the lower part of the Westwater Canyon sandstone and underlying Summerville, Entrada, Carmel, and Wingate units. In Sample 21 from the Westwater Canyon sandstone member the light-mineral suite was 17 percent feldspar. Micrographic intergrowths of orthoclase and quartz were observed in Samples 37 and 38 from the Dalton sandstone tongue.

Quartz. Quartz in various forms makes up the bulk of most of the sampled section. Much of the quartz contains inclusions; differences in the nature of these inclusions were noted. In the sampled section most of the inclusions are needles, vacuoles, or fluid bubbles. These types Mackie (1896) demonstrated were of igneous origin. Inclusions are absent in the quartz of Sample 22 from the Westwater Canyon sandstone and Sample 31 from the Mancos shale, which suggests that this quartz was derived from metamorphic rocks. Quartz of mixed metamorphic and igneous types was observed in Samples 23 and 24 from the Westwater Canyon sandstone member, and in Sample 15 from the Chinle formation.

Secondary enlargement of clastic quartz yielding doubly terminated euhedra is common in the sampled section. Typically the external faces of these euhedra are in optical continuity with the nucleus, but at places secondary quartz occurs as a drusy growth without relation to the optical orientation of the nuclei.

A small amount of secondary enlargement occurs on the quartz in the Chinle formation and Wingate sandstone; none was observed in the Carmel, Entrada, or Summerville units. Secondary enlargements on quartz are very abundant in the upper part of the Westwater Canyon and Dakota (?) sandstones. A small amount occurs in the Gallup sandstone, Dilco member of the Crevasse Canyon formation, and lower part of the Point Lookout formation.

The observed vertical distribution of secondary enlargements on quartz suggests that the presence or absence of the enlargements probably will be of little help in differentiating these sediments.

Angularity

Angularity measurements recorded in Plate 14, Column D, are based on measurements made on the .125-mm size fractions of the light-mineral suites. Angularity increases markedly above the

Dakota (?) sandstone; at places it exceeds 70 percent. A similar abrupt increase in angularity occurs at the top of the Chinle formation.

Differential Thermal Analyses

The potential value of clay mineralogy as an aid in stratigraphic differentiation and correlation was pointed out by Kauffman (1948). The results of a preliminary investigation of the value of differential thermal analyses as a means of subsurface stratigraphic correlation were published by Romo (1950). As a result of this preliminary investigation it appears that formation changes are often indicated by changes in the shapes of the differential thermal curves.

The present study has corroborated the findings of Romo. Plate 13 illustrates graphically the differences observed in the differential thermal analyses of the silt-clay fractions in the sampled section. The curves have been divided into groups, each group being made up of curves having approximately the same sequence of endothermic and exothermic peaks; the peaks in each group are of about the same amplitude.

The grouping of the thermal curves must for the present be largely empirical. However, several of the clay-size samples have been examined with the electron microscope, with X-ray, and by staining tests. These examinations will be continued and the clay minerals present in the samples will be reported in more absolute terms later.

Group I includes samples from the Cutler formation, De Chelly sandstone, and the Shinarump conglomerate. All the curves in this group have broad, low-amplitude endothermic peaks at 100°-120°C and at 550°-575°C. The amplitude of the 100°-120°C peak increases very gradually upward in Group I. The curves for Samples 5 through 9 are similar to standard curves for montmorillonite, differing mainly in the intensity of the recorded reactions. The differences in intensity may have resulted from differences in the degree of crystallinity or dilution.

Samples I through 3 of Group I did not react to colorimetric benzidine tests for montmorillonite; above Sample 3 the reactions were strong. This difference in reaction to benzidine may furnish a means of distinguishing between the Cutler formation and the De Chelly sandstone. Lithologically the two are gradational.

The gradual increase in the intensity of the thermal reactions toward the top of Group I continues into Group II, consisting of the Chinle formation; in addition the low temperature peaks change to doublets, with maxima at 120°C and 200°C. The high temperature peaks in Group II are somewhat sharper and have shifted toward 600°C. Positive colorimetric benzidine reactions for montmorillonite were obtained on all samples of Group II, but were strongest on Samples
14 and 15.

Staining tests with safranine Y and malachite green were negative for all samples from Groups I and II, with the exception of Samples 14 and 15 at the top of the Chinle formation, which gave distinct montmorillonite reactions.

The broad endothermic peaks between 500°C and 600°C in

Groups I and II may be due in part to the presence of illite or mixed layer days. Hence the observed difference between the thermal curves of Groups I and II may be largely the result of differences in the relative amounts of montmorillonite, illite, or mixed layer clay. The clay mixtures in Group I may be mostly illite and in Group II mostly montmorillonite.

Group III includes all the Jurassic formations of the sampled section except the Westwater Canyon sandstone member of the Morrison formation. The thermal curves of this group all have strong endothermic peaks between 100°C and 120°C, but beyond this there is little similarity between them. The mineralogic reasons for the observed differences are not clear, but if persistent they would be adequate to differentiate these Jurassic formations. Additional studies of a completely exposed section of these rocks are needed.

Between Groups III and IV there is an abrupt change in the shape of the curves. In Group IV the endothermic peaks between 100°C and 120°C are very much reduced and a sharp peak appears at about 550°C. The amplitude of the 550°C peak is much greater for samples from the top of the group. The shape of the curves in Group IV suggests that the samples contain a mixture of montmorillonite and kaolinite, kaolinite being by far the more abundant. Group IV represents only part of the Westwater Canyon sandstone; it does not include Sample 23 from the top of the formation.

The thermal curve for Sample 23, Group V, differs markedly from the curves above and below it. A broad, low exothermic peak occurs between 300°C and 400°C, and this is followed by an endothermic doublet, with maxima at 530°C and 630°C.

The thermal curves for Samples 25 ss, 25 sh, and 26 from the lower part of the Dakota (?) sandstone make up Group VI. All the curves of this group have large endothermic peaks at 550°C. An exothermic peak between 650°C and 700°C on the curve of Sample 25 sh suggests the presence of siderite, but the presence of this mineral was not indicated on X-ray-diffraction pictures. The clay in this group appears to be largely kaolinite.

The upper half of the Dakota (?) sandstone and all of the Mancos shale are included within Group VII. The curves of this group are similar to the curve of Group V. An endothermic doublet, with maxima at approximately 530°C and 630°C, is present in all the curves. Small endothermic peaks, not present in Group V, occur between 100°C and 200°C in the two uppermost curves of Group VII. The shape of the curves in this group suggests a mixture of illite, kaolinite and montmorillonite. Montmorillonite is probably most abundant in Sample 31. Illite in these samples has been tentatively identified by X-ray and stain tests.

Above the Mancos shale the differences between the groups of thermal curves are not great. With the exception of Group IX, which includes the Dalton and Hosta sandstone tongues, most of the curves appear to represent mixtures of kaolinite and montmorillonite, in which kaolinite is the dominant mineral. The samples of Group IX probably contain illite in addition to the kaolinite and montmorillonite.

CONCLUSIONS

No very significant heavy-mineral data were obtained from the Chinle formation or De Chelly sandstone. The slight information available suggests that the De Chelly sandstone was derived from a distributive province in sedimentary rocks. The differential thermal curves may provide a clue to the history of these deposits. The uniformity of the curves suggests that these formations are the result of uninterrupted sedimentation. They may be the product of a single distributive province or persistent combination of provinces. The presence of illite might be interpreted as indicating that these sediments were deposited in a marine environment. It should be pointed out, however, that the clay minerals, particularly in nonmarine sediments, may be inherited in part from their distributive province. Van Houten (1953) has demonstrated that clay minerals in soils may be inherited from the parent material.

The changes in mineralogy between the De Chelly sandstone and Chinle formation are marked. Epidote and biotite appear, fragments of volcanic rock are present, montmorillonite becomes the principal clay, and the coefficient of sorting increases sharply. On the basis of these observations it is concluded that the Chinle in this area is a mixture of volcanic and nonvolcanic material. In the sampled section this mixing was not megascopically evident. Waters and Granger (1953) have reported a similar mixed origin for the Chinle formation in other parts of the Colorado Plateau.

The abundance of montmorillonite at the top of the Chinle formation, as revealed by the thermal analyses and colorimetric tests, would appear to offer an excellent means of recognizing this formation, both in surface exposures and well cuttings.

The Jurassic sediments between the Wingate sandstone and Sample 23 of the Westwater Canyon sandstone member have many of the features of the sediments both above and below them. However, the presence of unstable heavy minerals, the abundance of feldspar, and the slightly greater angularity make these rocks distinguishable from the overlying strata.

The thermal curve for Sample 24 from the top of the Westwater Canyon sandstone member is markedly different from the other curves representing this sandstone. The thermal curve for Sample 24 is closely similar to the curves for the upper part of the Dakota (?) sandstone and Mancos shale. These thermal curves may be indicative of the history of the formation; in this area the upper part of the Westwater Canyon sandstone member probably is a product of the same sedimentary processes that produced the upper part of the Dakota (?) sandstone and the Mancos shale.

No major break in the mineralogy occurs across the contact between the Westwater Canyon and Dakota (?) sandstones in the sampled section. This is remarkable, if that contact represents a major unconformity.

Strata from the upper part of the Westwater Canyon sandstone member through the lower part of the Mancos shale contain a monotonous and restricted heavy-mineral suite consisting largely of such stable minerals as tourmaline, zircon, and garnet. Most of the grains are rounded; the tourmaline is typically very highly polished. Above the Mancos the heavy-mineral suite is less restricted; chlorite, biotite, titanite, and zoisite are present. Also, the amount of feldspar, and muscovite, and the degree of angularity increase markedly. The clay-mineral assemblage changes as well.

The above observations indicate clearly a change in the character of the distributive province. The mineralogy of the rocks from the upper part of the Westwater Canyon sandstone member, through the lower part of the Mancos shale, appears to be the remains of preexisting sediments. Above the Mancos they appear to have been in part derived from a crystalline source. The absence of inclusions in some of the quartz grains of this part of the section suggests that the crystalline source was a metamorphic terrane. It may be inferred that during the accumulation of the Cretaceous sediments progressive denudation of the distributive province exposed the crystalline core, or that for a time the sediments were contributed by two distributive provinces, one sedimentary, the other crystalline. In either event the observed change in the mineralogy of these rocks may prove to have a restricted range in time, and hence be an aid in lateral correlation of these sediments.

SEISMIC RECONNAISSANCE SURVEY IN BUELL PARK

by Robert Sykes and E. R. Harrington

A seismic reconnaissance survey was made in the Buell Park area. Calibration base lines were first run on the Precambrian quartzite outcrop in Bonito Canyon and on the De Chelly Permian sandstones, both near Sawmill and on the rim of Buell Park, and two lines were then run on the kimberlite and lapilli tuffs in the bottom of Buell Park. The refraction data from these lines yielded a velocity of about 15,500 fps for the quartzite, velocities of 12,000-13,000 fps for the De Chelly sandstone, and velocities of from 5,000 to 6,000 fps for the volcanic tuffs in the Buell Park caldera.

Calculations based on the attitude of the Precambrian quartzite outcrop, and the depth of this quartzite in several wells in the area surrounding Buell Park, reveal that 800-900 feet of De Chelly sandstone overlies the quartzite in the section on the rim of Buell Crater. The depth to the Precambrian quartzite, together with the small velocity contrast between the sandstone and the quartzite, excluded the use of the refraction method for determining the surface of the Precambrian quartzite, owing to the shortness of the maximum spread length (2,500 feet) obtainable with the equipment used. Moreover, the depth to the quartzite is such that any reflected waves coming from it would arrive at the same time as the stronger ground waves and be submerged in them. The records of the line run on the rim showed no reflections. Two lines were run in the caldera to see if it bottomed; however, no reflections were observed.

The reconnaissance survey along the rim shows this area to be impracticable for either reflection or refraction seismic work to determine the surface of the Precambrian rock, unless some method of eliminating the response of the ground wave is devised.

Supplementary Data and Glossaries

CLIMATIC DATA

Two weather stations, at Fort Defiance and Tohatchi, are located within the area. Records from these stations, given in Table 19, furnish an idea of the average climate for the lower parts of the area; in higher regions the climate is more severe. Three other stations outside the area, at Chinle, St. Michaels, and Gamerco (north of Gallup), add to the regional picture.

TABLE 19. CLIMATIC DATA (from *Climate and Man*, House Doc. No. 27, 1941 Yearbook of Agriculture, pp 1013, 761)

	Tohatchi*	Ft. Defiance	Chinle	St. Michaels	Gamerco*
Elevation	6,450′	6,750′	5,538′	6,950′	ca. 6,550′
Temperature (°F)					
Length of record (years)	24	17	21	20	28
January average	30.7	25.6	27.9	27.6	26.7
July average	73.4	68.5	74.0	69.5	70.0
Maximum	101	98	103	106	98
Minimum	−10	−30	−32	−25	−20
Average Precipitation (inches)					
Length of record (years)	27	16	21	21	28
January	.70	.78	.41	.96	.61
February	.60	1.27	.60	.98	.85
March	.59	.83	.53	.95	.89
April	.50	.75	.41	.51	.70
May	.81	.64	.30	.38	.77
June	.50	.82	.46	.43	.42
July	1.41	1.53	1.70	2.44	1.70
August	1.60	2.08	1.36	2.39	2.35
September	1.44	1.33	1.07	1.32	1.52
October	.89	.51	.76	1.11	.91
November	.55	.85	.39	.68	.68
December	.63	.73	.61	1.01	.79
Annual	10.22	12.12	8.60	13.16	12.19
Killing frost, average dates					
Length of record (years)	15	15	22	21	17
Last in spring	May 3	May 26	May 23	May 21	May 11
First in fall	Oct 19	Sept 30	Oct 5	Oct 1	Oct 8
Growing season (days)	173	127	135	133	150

* Brought up through 1950, courtesy of Weather Bureau, Albuquerque office.

SELECTED STRATIGRAPHIC SECTIONS IN PERMIAN AND JURASSIC FORMATIONS, FORT DEFIANCE QUADRANGLE

by Robert Balk

SECTION 1 UPPER CUTLER FORMATION AND DE CHELLY SANDSTONE

Measured at the southeast corner of Buell Park. Measured with tape.

DESCRIPTION	THICKNESS IN FEET
Shinarump conglomerate at top	
Upper De Chelly sandstone, strongly crossbedded, tan and pale pastel-brick, fine-grained, feldspathic	226
Light brick to tan, crossbedded sandstone in 2-4 ft crossbed units. Above this member, the rock breaks up into 1-4 in. slabs	33
Strongly crossbedded sandstone, of same color as below, but makes steeper cliff on entire slope	29
Crossbedded, massive and homogeneous-weathering, pastel-brick, pastel-maroon sandstone, making slope of 22-28 degrees	52
Flaky, dark brick-red, soft zone	1.5
Firm, crossbedded pale brick-red sandstone	18.5
Pastel-maroon, more shaly sandstone than beds below, makes no persistent depression. Above this layer the solid lower slope of the section begins	5
Pastel-maroon fine-grained sandstone	15
Maroon, flaky, relatively soft sandstone. Makes slight depression in slope	5
Pinkish-cream, strongly crossbedded sandstone, tops the lowest, relatively steep sandstone bluff	3
Maroon, shaly, flaky lenticular sandstone	2
Fine-grained pastel-maroon sandstone	22
Slightly crumbly, maroon shaly sandstone	5
Firm pastel-maroon sandstone. This is the lowest resistant zone in profile. It starts the main sandstone slope	14
Maroon, flaky soft sandstone	6
Pastel-maroon resistant sandstone. Upper 8 in. flaky and darker. At top a white 4-in. sandstone bed	6.5
Maroon, shaly, flaky sandstone	1.5
White bottom sandstone bed	6
Total thickness of De Chelly sandstone	259
Total thickness of upper Cutler formation (above shales)	192

SECTION 2 UPPER CUTLER FORMATION AND DE CHELLY SANDSTONE

East slope of Piney Hill Lookout, southwest corner of Fort Defiance quadrangle, Arizona-New Mexico. Measured by tape.

DESCRIPTION	THICKNESS IN FEET
Tan and salmon, crossbedded feldspathic sandstone. Top not exposed. Upper De Chelly sandstone	167
Tan and pale brick-red crossbedded feldspathic sandstone. Weathers in steep cliff. Lower De Chelly sandstone	114
Total	281
Poorly cemented, crossbedded, pale-maroon friable sandstone. Weathers either as gentle slope with few outcrops, or may form relatively steep slope with numerous ledges, leading up to the lower De Chelly scarp	38

Description	Thickness in Feet
Crossbedded, pale-maroon sandstone. Makes strong upper Cutler ledge	39
Maroon, shaly sandstone, weathers as soft bed	6
Pale-maroon, crossbedded sandstone, relatively resistant. Upper 2 ft pass gradually into overlying beds	11
White, crossbedded sandstone	1.5
Maroon, shaly sandstone, weathers relatively soft	15
Pastel-maroon, crossbedded sandstone, weathers strong. Upper 2 ft are white, underlie a shaly zone	38
Brown shale, sandy, not persistent	1.5
Sandstone	7
Upper chocolate-brown, persistent shale bed	8
Pastel-maroon sandstone	13.3
Lower chocolate-brown shale zone. Lower 4 ft are relatively sandy. At bottom and top 4-in. sandstone bed, persistent	9
Sandstone as below; shaly zone 1½ ft thick near bottom	10
Dull-maroon sandstone, crossbedded	30.5
Total	227.8
Total section (511 ft by altimeter)	508.8

Section 3 De Chelly Sandstone

North wall of Bonito Canyon. Measured section starts about 300 ft east-southeast of place where dirt road crosses irrigation ditch.

Description	Thickness in Feet
Shinarump conglomerate at top	
Pale-brick sandstone, somewhat softer than the firmer beds below and slightly darker. Commonly a 10-ft brown, relatively hard, bed just below the Shinarump. Locally, 2-4 ft of brick-red shaly beds lie above and directly below the Shinarump	92
Pale-maroon, buff to tan, crossbedded sandstone. In upper 30 ft there are 3 strong, 2-4 ft layers, separated from each other by darker, pale-maroon, shalier, soft zones	97
Salmon, pinkish, pale brick-red sandstone. Section rests on 20 ft of heavy-bedded, crossbedded, massive-weathering sandstone, believed to be uppermost Cutler	110
Total thickness of De Chelly sandstone	299

Section 4 Wingate Sandstone and Carmel Member of Entrada Formation

Measured from top of Chinle limestone pebble-conglomerate layer, east base of great promontory south of Twin Buttes Wash. Measured by tape.

Description	Thickness in Feet
Steep cliff of upper Carmel brick-red sandstone, with characteristic cracks. Overlain by Entrada sandstone	85
Soft brick-red argillaceous sandstone, overrolled by talus	62
Wingate brick-red, crossbedded, feldspathic sandstone. Upper 8 ft locally particularly strong. Makes vertical cliff	39
Cliff-forming brick-red sandstone, but weaker than overlying beds	16
Brick-red, flaky sandstone, underlies foothill slope to Wingate cliff	28
Covered interval on top of lavender limestone-pebble conglomerate bed. Makes flat grassy surface	56
Total interval between limestone-pebble conglomerate bed and base of Entrada	286

SECTION 5 WINGATE SANDSTONE AND CARMEL MEMBER OF ENTRADA SANDSTONE

North-northeast end of plateau west of Todilto Park.

DESCRIPTION	THICKNESS IN FEET
Entrada sandstone cliff at top	
Typical Carmel; knobby-weathering, oddly jointed, brick-red, locally crossbedded, feldspathic sandstone	62
Lower Carmel or upper Wingate. Soft-weathering brick-red to paler pinkish thin-bedded shaly sandstone	26
Main vertical cliff of strong Wingate sandstone	20.5
Brick-red, shaly sandstone; top 18 in. is locally a deep chocolate-brown, softer sandy shale. Bed as a whole is well cemented and forms locally vertical cliff	17
Uniform, thin-bedded, brick-red shaly sandstone, makes straight 36-degree slopes	13
Stronger brick-red sandstone bank	2
Red, thin-bedded shaly sandstone with many gray, bleached spheres, 2-3 mm across	15
Harder sandstone bank	2
Slightly stronger sandstone than underlying beds. Brick-red, shaly	10
Soft earthy sandy shale, makes relatively gentle slopes	20
Base of lowest beds may be 80 ft above Chinle clay	
Total measured interval (exclusive of the lowest 80 ft) below base of Entrada	187.5

SECTIONS 6 TO 9 ENTRADA SANDSTONE (EXCLUDING CARMEL)

DESCRIPTION	THICKNESS IN FEET
At "Haystacks," along cross-section B-B′, due east of Fort Defiance	208
On north side of Twin Buttes Wash canyon	205
On north-northeast corner of western block, Todilto Park	153
On southern border of Green Knobs tuff pipe (incomplete)	129

SECTION 10 SUMMERVILLE FORMATION

South side of Zilditloi Canyon.

DESCRIPTION	THICKNESS IN FEET
Lower Morrison (Cow Springs sandstone) at top	
Pale-pink, massive-weathering and bluff-forming crossbedded sandstone. Top 15 ft quite massive, weathers into polygons	32
Pastel-raspberry to pinkish-gray, soft sandstone, crossbedding hard to see. Only a few 3-6 in. layers make low ribs in outcrops	30
Partly covered, flat zone of pale brick-red to cream-raspberry, relatively massive, crumbly sandstone	21
Gray to pinkish, crossbedded sandstone, weathers relatively resistant	15
Maroon, dark-rusty sandstone, terminates the top of the polygons	1
Cream-pinkish, crossbedded polygonally-weathering sandstone	14
Grayish to pink, crossbedded sandstone in ½-1 ft beds. Appears to be the lower portion of the polygon beds	26
Main Summerville cliff, of brick-red to pale gray-maroon, rarely crossbedded sandstone	46
Soft-weathering brick-red shaly sandstone, of 1-3 ft beds. Partly covered	22

DESCRIPTION	THICKNESS IN FEET
Steep cliff of brick-red and grayish-pink, moderately crossbedded sandstone; mostly 1-3 ft beds	18
Dark brick-red sandstone, at base of steep cliff, but easily weathering itself. Resembles "Carmel" weathering	5.5
Soft-weathering 1-3 in. brick-red sandstone	12
Cliff-forming brick-red sandstone in ½-1 ft beds, moderately crossbedded	34.5
Soft-weathering pink or brick-red, crossbedded sandstone in 1-2 in. beds	29
Hard pink sandstone bank, crossbedded	1
Pink or grayish-pink, crossbedded sandstone, in 1-4 in. beds. Makes a few low ribs	21
Covered interval at base; pale pinkish-gray, thin-bedded, crossbedded sandstone	39
Entrada sandstone at base	
Total thickness of Summerville formation	367

SECTION 11 MORRISON FORMATION

Measured in westernmost of the several ravines on south slope of Zilditloi Mountain.

DESCRIPTION	THICKNESS IN FEET
Basalt talus, possibly including Dakota (?) sandstone blocks	about 100
Tan, buff sandstone, as debris in basalt talus	78
Chocolate-brown clay	3
Orange, resistant, crossbedded arkosic sandstone	87
Same as above	54
Chocolate-brown shale lenses	2.5
Pale-orange, dull-buff, cliff-forming gritty arkose, crossbedded, with many dull grayish-brown liesegang rings	33
Chocolate-brown clay, canary-yellow at top 4 in.	3
Pale yellow-gray sand	7
Pale cream-pink, crossbedded sandstone, at top with 20 smoky ¼-in. layers	11
Shale, brown, yellow, light-gray, with sandstone lenses, 3-4 in. thick	4
Pale-buff arkose, poorly cemented, heavy-bedded, crossbedded	18
Pale-tan, cream-pink, crossbedded, arkosic sandstone, with a few pale-green 1-in. streaks	25
Chocolate-brown shale	12
White sand	11
Brown clay	2
White sand	17
Brown clay	1
White sand	18
Chocolate-brown to maroon shale	16
White or cream-colored sand	5.3
Main cliff-forming series of pale grayish-pink soft sandstone in 1-3 ft crossbeds. In middle a pastel-pink, massive 7-ft grit bed. Thin gray interbeds in upper 20 ft	84
Massive gray-maroon "grit" bed, with abundant quartz, chert, and fresh feldspar debris, 1-3 mm across. Also coarser aphanitic whitish or cream-colored chips, 5-9 mm	8
Soft-weathering, pink, grayish-pink sand, locally sandstone	19
Gray sandstone	1
Chocolate-brown shale	1.6
White fine-grained sandstone	.5
Brown, clayey sand, with several 2-in. zones of white dense concretionlike stones	11.5
Brown clay	9

Description	Thickness in Feet
Gray, rarely pinkish, punky, heavy-bedded, crossbedded sandstone. Top 6 ft a uniform pink, massive-weathering bed. Lower 40 ft are maroon, heavy-bedded, crossbedded sandstone. Base not directly exposed on north wall of canyon, but error cannot be great	46.7
Total measured thickness of Morrison formation	589

Section 12 Morrison Formation

North of Twin Buttes Wash.

Description	Thickness in Feet
Dakota (?) sandstone cliff. Crossbedded, hard, pale-yellowish to gray sandstone, with several "chicken grit" lenses, but no larger pebbles here. Some feldspar debris. Many holes in cliff surface	20+
Violet sandstone	.2
Crossbedded, white, raspberry, lavender, feldspathic soft sandstone, harder and bluff-forming in upper 12 ft, and there with pebble lenses. Quartz debris, 3-4 mm, common	27
Shaly sand, loose, green and maroon	29
Orange, coarse, crossbedded sandstone. Single pebbles up to 3 in.	55
Chocolate-brown shale	2
Orange, bluff-making, crossbedded, fine-grained feldspathic sandstone	89
Covered interval, underlain mostly by yellowish to pale whitish-gray sand	156
Pinkish, white, crossbedded sand, with 4 or more 6-in. zones of deep-green sandstone, surrounded by 1-in. brown, yellow, or maroon beds	31
Sand as underlying beds, with irregular pink blotches	4
Slightly greenish, white, or light-gray sand. At top a few pale-green concretions	24
Chocolate-brown clay	7
White or very pale pinkish, crossbedded, fine-grained sandstone	49.5
Pale-pink to raspberry, compact-weathering, heavy-bedded sandstone. Locally as 4-6 in. white beds. Makes smooth bluff	61
Dominantly gray, or very light pink, compact, fine-grained sandstone	53
Light-gray. pinkish, bluff-making, heavy-bedded sandstone. A few conglomeratic lenses with cherty pebbles, 3-4 mm across	128
Crossbedded, relatively soft, gray to pale-maroon sandstone. Heavier beds at top, 4-6 ft thick. Zone makes 37-degree smooth slopes, with disintegrated rocks	94
Summerville formation at base	
Total thickness of interval between Summerville formation and Dakota (?) sandstone	809.7

Section 13 Morrison Formation

South side of Twin Buttes Wash.

Description	Thickness in Feet
Dakota (?) sandstone. Slightly yellowish-gray, coarse, sharp gritty sandstone, crossbedded, very cavernous. Many sharp or round translucent quartz grains, 1 mm diameter, and very little feldspar. Crossbedding commonly on a 1-2 in. scale.	
Covered interval to base of Dakota (?) sandstone cliff. Brown shale, at east in part	about 26
Cliff-forming arkose, orange-pink, gritty, with many 1-2 mm fragments, and some pebbles up to 4 in. across. Abundant feldspar debris; crossbedded throughout. Carries many lenses of	

Description	Thickness in Feet
clay-shale, chocolate-brown, with marginal yellow, greenish, or gray zones, and contains dark-green chloritic sandstone lenses	148
Brown sandy shale	4
Pink arkosic sand	3
Pale-maroon to pinkish arkose, locally poorly cemented. Sharp sand, with generous admixture of single pebbles, 5-10 mm in diameter	36
Light-gray clayey sand, slightly greenish	6
Chocolate-brown shale	.5
Pink sharp sandstone, locally uncemented	8
Pink sharp sand, locally cemented, with sparse fragments, 2-3 mm in diameter, and some feldspar debris. At top of this zone, the slope steepens markedly	37
Pink to light-gray sand. This is top member of the soft-weathering middle Morrison (Recapture shale) group. Above, slope steepens toward the big top cliffs	19
Brown clay, near top with two 1-ft zones, sandy, light-gray	15
Greenish light-gray sand	3
White clayey sand	11
Light-brown sandy clay	7.5
Light-gray clayey sand	5
Brown shale	3
White clayey soft sand, makes miniature badland topography	20
Chocolate-brown shale, in spots dirty-yellowish	11
White or light-gray, crossbedded friable sandstone. Makes same kind of smooth slope as underlying unit	88
Pink and gray crossbedded sandstone, with occasional grit zones, and single pebbles, 3-4 mm across	46
Gray, pink, and buff sandstone, fine-grained, crossbedded. Makes smooth, strong slope of 21 degrees. Above this unit, grit zones appear	62
Buff, gray, 2-in. sandstone beds interbedded, crossbedded	6
Relatively shaly zone with 3-4 mm calcareous concretions	1
Strong, massively bedded pale grayish-pink sandstone. Makes rib	16
Pale brick-red argillaceous sandstone	51
Strong pale-pink massive rib-making sandstone	11
Pinkish, gray, fine-grained, crossbedded sandstone. Some 1-2 ft zones more argillaceous. Few ribs in this zone	53
Grayish-pink, relatively massive, crossbedded sandstone	8
Maroon, relatively argillaceous sandstone; small-scale wavy cross-bedding	15
Brick-red shaly bed	1
Pale grayish-brick, fine-grained, crossbedded sandstone in 1-2 ft crossbeds	16
Top of polygonally weathering sandstone of Summerville formation	
Total thickness of Morrison formation	737

Section 14 Middle and Upper Morrison Formations

West-facing scarp, ½ mile north of Clay Springs Wash.

Description	Thickness in Feet
Dakota (?) sandstone on top, weathering a relatively somber shade of smoky rusty-orange. Lichen coatings add to the relatively dark colors, in comparison with the underlying Morrison sandstone series. Bottom 1 ft of Dakota (?) here is dark-gray shale	20+
Pink and reddish-orange, sharp, gritty, crossbedded sandstone, with lenses of clayey sand, ½-2 ft thick, of purple, greenish,	

Description	Thickness in Feet
and light yellowish-gray color, irregularly blending with the sandstone. A pale yellow is common in upper 30 ft of this sandstone zone. Single pebbles in this zone, of granite, various fine-grained crystalline rocks, chert, etc., go up to diameters of 4 in. Near top, a few lenses of pale-gray grit resemble the Dakota (?) sandstone	39
Punky, gray, pink, yellowish-gray, crossbedded sandstone, with indistinct, ill-defined, more argillaceous lenses of the same colors. Occasional single pebbles can go up to diameters of 1 in.	95
Pinkish or yellowish clayey sand	9
Purple sandy clay, more grayish at top 2 ft	13
Pale grayish-yellow sharp, crossbedded sandstone	5
Orange-pink, crossbedded gritty sandstone. Upper 10 ft of paler color, more grayish-yellow. Locally, 1-ft lenses of pale-purple sandy clay in this unit, with greenish sand	70
Pale-purple, pale-green sand, clayey. Soft, lenticular horizon	17
Orange-red, pinkish, crossbedded gritty sandstone	41
Pale-green, maroon, and white sandy clay, or clay lenses. Soft horizon, undermines cliff next above	3
Ruddy-pink, "wavy" crossbedded, sharp sandstone, with several 1-in. maroon crossbeds, also local pale-greenish streamers. Debris, ½-1 mm across not rare, some is feldspar	22
Base concealed by weathered soil and talus debris.	
Exposed, partial thickness	314

SELECTED STRATIGRAPHIC SECTIONS IN THE MENEFEE AND CREVASSE CANYON FORMATIONS

by John Eliot Allen, Brewster Baldwin, and John Hill

Section 5 (pl 11) Menefee Formation

Measured eastward toward Chuska Peak from a point 1 mile west of Mexican Springs Wash to a point just west of small triangular peak, 2 miles west of Chuska Peak. Plane table traverse and tape.

Unit No.	Description	Thickness in feet: of unit	Thickness in feet: from base
50	Cliff-making yellowish gray (5Y7/2) friable massive sandstone	20	1479
49	Variegated siltstones and shaly siltstones	190	1459
48	Cliff-making yellowish-gray (5Y7/2) friable massive sandstone	25	1269
47	Variegated gray, yellow, dusky-orange (5Y5/2 to 10Y6/2) medium- to fine-grained sandstones and siltstones with some shale. Poorly cemented, vertebrate fossils near base	92	1244
46	Brown (5YR5/4) iron-cemented concretionary sandstone	2	1152
45	Grayish-orange (10YR7/4) medium- to fine-grained sandstone, forming cliff	23	1150
44	Similar to No. 47 above	42	1127
43	Grayish-orange (10YR7/4) friable sandstone	10	1085
42	Similar to No. 47 above	54	1075
41	Cliff-making yellowish-gray friable sandstone with brown iron-cemented concretions at top	20	1021
40	Similar to No. 47 above	160	1001

Unit No.	Description	Thickness in feet: Of unit	From base
39	Cliff-making yellowish-gray (5Y7/2) thin-bedded friable medium- to fine-grained sandstone with iron-cemented concretions at top	15	841
38	Lens of dark-gray medium-grained limestone	1	826
37	Dusky-yellow (5Y6/4) silty shale	50	825
36	Gray clay shale	2	775
35	Grayish-orange silt with numerous platy limonite veinlets	3	773
34	Pale grayish-yellow (5Y8/4) friable sandstone	7	770
33	Grayish-orange (10YR7/4) fairly well-cemented sandstone	8	763
32	Gray clayey siltstone and shale (mostly covered)	15	755
31	Pale grayish-yellow silty sandstone (mostly covered)	40	740
30	Grayish-orange (10YR7/4) medium- to fine-grained sandstone forming cuesta	30	700
29	Ocherous clay	1	670
28	Grayish clay, siltstone and shale	40	669
27	Cliff-forming pale-yellow friable sandstone	10	629
26	Dusky-yellow (5Y6/4) friable siltstones and shales	118	619
25	Cliff-making dark yellowish-orange (10YR6/6) massive, medium- to fine-grained arkosic sandstone, lower part crossbedded, upper part channel fill	40	501
24	Gray platy clayey siltstone with leaf imprints	4	461
23	Yellow to yellowish-orange crossbedded, laminated medium- to fine-grained, poorly cemented sandstone, with iron-cemented layer at top	14	457
22	Olive-green to dusky-yellow silty shale	32	443
21	Dark-brown iron-cemented concretionary sandstone	6	411
20	Cliff-making yellow to yellowish-orange, crossbedded, finely laminated, medium- to fine-grained poorly cemented sandstone	14	405
19	Olive-green to dusky-yellow silty shale	60	391
18	Covered. Probably shale as above	146	331
17	Cliff-making grayish-yellow, massive, friable silty sandstone with brown iron-cemented cap-rock	20	185
16	Brown iron-cemented sandstone	6	165
15	Grayish-yellow friable sandstone	10	159
14	Covered	44	149
13	Cliff-making pale-yellow friable sandstone with iron-cemented cap 6 inches thick	18	105
12	Fissile gray shale	2	87
11	Fissile dark-gray carbonaceous shale	2	85
10	Coal, with several thin layers of carbonaceous shale	6	83
9	Gray, silty carbonaceous shale	2	77
8	Clayey lignite or bone	1	75
7	Bright coal	2	74
6	Carbonaceous shale	5	72
5	Friable grayish-orange sandstone	3	67
4	Yellowish-orange well-cemented sandstone	3	64
3	Pale to dark yellowish-orange crossbedded friable sandstone	5	61
2	Olive-brown shale	7	56
1	Covered, probably shale with one coal bed	49	49

Top of Point Lookout sandstone

This section contains 1129 ft of siltstone and shale and 349 ft of sandstone, or 23.5 percent sandstone.

Section 6 (pl 11) Menefee Formation

Measured from the mouth of Crevasse Canyon, above the Soil Conservation Service weir, to a point 500 feet north of the road at the summit east of Mexican Springs Wash. Plane table traverse and tape.

Unit No.	Description	Thickness in feet of unit	Thickness in feet from base
102	Cliff-making sandstone, thinning rapidly to the north; laminated grayish-orange (10YR7/4) medium- to fine-grained. 70 percent rough-surfaced quartz, 15 percent feldspar, in matrix of clay with some rock fragments and mica. Cementation fair, of iron oxide and clay; jointing poor, some iron oxide concretions. Base sharp and even	33	1160
101	Gray clay shale	1	1127
100	Olive-green to olive-gray (5Y6/4 to 5Y5/2) silty clay and siltstone	39	1126
99	Dark-brown iron-cemented medium-grained sandstone with platy crosslaminations. Thickens northward to 20 feet within 200 feet	13	1087
98	Gray siltstone	15	1074
97	Olive-colored silty shale	30	1059
96	Pale-yellow siltstone	10	1029
95	Pale-gray, platy, crossbedded clayey sandstone with iron-cemented cap from 2 to 3 feet thick	6	1019
94	Yellow and gray siltstone and shale	18	1013
93	Cliff-making grayish-orange (10YR7/4) homogeneously colored, poorly cemented and friable, massive, medium- to fine-grained quartz (70 percent) sandstone, with some feldspar (5 percent), rock fragments (5 percent) and clay matrix. Base gradational into #92 below	15	995
92	Olive (10Y5/2) clayey siltstone	18	980
91	Olive-gray (5Y3/2) shale	3	962
90	Olive clayey siltstone	27	959
89	Cliff-making dark yellowish-orange (10YR6/6) lens of medium-grained quartz (90 percent) sandstone with rock fragments (5 percent) and clay matrix. Well sorted, sub-angular, rough grain surfaces, friable. Thickens to north	4	932
88	Carbonaceous shale and clay shale with grayish-red (5R4/2) silty sandstone at base	3	928
87	Gray silty shale	6	925
86	Olive silty shale	19	919
85	Light-brown (5YR5/6) crosslaminated, platy-weathering, iron-cemented sandstone	4	900
84	Pale greenish-yellow (10Y8/2) medium- to fine-grained very friable quartz (80 percent) sandstone with some clay, rock fragments and ferro-magnesian minerals	5	896
83	Light olive-gray (5Y5/2) silty shale and siltstone	50	891
82	Pale-yellow (10Y8/2) siltstone	10	841
81	Light-brown (5YR5/6) iron-cemented sandstone lens	4	831
80	Covered, probably sandy siltstone	18	827
79	Light olive-gray (5Y5/2) silty shale, slightly bentonitic	8	809
78	Clayey lignite with numerous rosin grains	1	801
77	Covered	9	800
76	Pale greenish-yellow (10Y8/2) fine-grained clayey siltstone	10	791
75	Dusky-yellow (5Y6/4) silty shale, mostly covered	105	781
74	Cliff-making grayish-yellow (5Y8/4) to pale yellowish-gray, thin-bedded, crosslaminated, platy, medium- to fine-grained silty sandstone. Top 4 feet brown, iron-cemented	13	676
73	Medium-gray (N6) silty sandstone	1	663
72	Yellow-gray (5Y7/2) silty, shaly sandstone	2	662
71	Medium-gray flaky clay	1	660
70	Yellow-gray silty, shaly sandstone	2	659
69	Medium-gray flaky clay	1	657
68	Yellow-gray silty, shaly sandstone	2	656
67	Grayish-black (N2) to medium-gray carbonaceous clay	5	654
66	Yellowish-gray (5Y7/2) fine-grained, silty, friable sandstone, with a few gray siltstone beds 3 to 6 inches thick	11	649

Unit No.	Description	Thickness in feet of unit	Thickness in feet from base
65	Medium-gray iron-stained siltstone and flaky clay	6	638
64	Yellowish-gray silty, fine-grained sandstone with a few gray siltstone beds	9	632
63	Cliff-making light-brown iron-cemented slabby sandstone	2	623
62	Grayish-orange (10YR7/4) massive cliff with color cross-laminations 3 in. to 3 ft thick, of medium- to fine-grained silty friable sandstone. Base sharp	11	621
61	Yellowish-gray, grading upwards to gray, clayey siltstone	7	610
60	Yellowish-gray fine-grained, silty, friable thin-bedded sandstone, lower contact sharp, upper contact gradational	5	603
59	Medium-gray shaly siltstone, carbonaceous fragments	4	598
58	Yellowish-gray fine-grained silty friable sandstone, base sharp	6	594
57	Yellowish-gray to gray, banded, massive to shaly siltstone, with 2 in. lignite 3 ft below top	24	588
56	Gray shale, with carbonaceous shale forming thin ledge 12 ft above base	18	564
55	Yellowish-gray, white-weathering, fine-grained silty sandstone	7	546
54	Medium-gray shaly clay, 6 in. of coal with gypsum fragments 1 ft from top	5	539
53	Yellowish-gray fine-grained silty, friable sandstone	9	534
52	Brown (10YR4/2) iron-cemented sandstone	3	525
51	Yellowish-gray (10YR7/4) fine-grained sandstone and siltstone	20	522
50	Gray shale	1	502
49	Yellowish-gray friable sandstone	10	501
48	Brown carbonaceous shale	1	491
47	Cliff-making brown (5YR5/4) iron-cemented sandstone, faintly crosslaminated	4	490
46	Yellowish-gray, friable, with faint crosslaminations, medium- to fine-grained sandstone with clay pebbles in basal 6 in.	10	486
45	Gray silty shale	2	476
44	Lignite	1	474
43	Yellowish-gray to gray clayey siltstone	2	473
42	Yellowish-gray medium- to fine-grained sandstone with clay pellets in basal 3 ft	13	471
41	Brown iron-cemented sandstone	2	458
40	Yellowish-gray friable sandstone	6	456
39	Covered	5	450
38	Gray shale, mostly covered	15	445
37	Yellowish-gray sandstone with minor shale partings, mostly covered	20	430
36	Brown iron-cemented sandstone	4	410
35	Cliff-making yellowish-gray, medium- to fine-grained cross-laminated sandstone	28	406
34	Yellowish-gray thin-bedded, lenticular sandstone with gray shale partings, lying in channels in underlying rock	10	378
33	Gray shale with thin sandstone lenses, finely laminated	5	368
32	Coal	2	363
31	Gray to dark-gray shale and carbonaceous shale	12	361
30	Yellowish-gray (5Y7/2) friable, medium- to fine-grained sandstone and siltstone	35	349
29	Medium-gray, fine-grained clayey sandstone, with some carbonaceous particles	1	314
28	Dark grayish-yellow (5Y7/4) friable, medium- to fine-grained silty sandstone	17	313
27	Covered	66	296
26	Yellowish-gray friable silty sandstone	5	230

Unit No.	Description	Thickness in feet of unit	Thickness in feet from base
25	Medium-gray to brownish shale and carbonaceous shale, with 3 in. of dark-brown to black iron-cemented sandstone at top	8	225
24	Light-gray friable sandstone and medium-gray shale, mostly covered, with 8 in. of lignite at top	6	217
23	Cliff-making light-gray shaly sandstone, with 4 in. of carbonaceous shale 1 ft above the base, and 6 in. of brown iron-cemented medium- to fine-grained sandstone at top	6	211
22	Yellowish-gray, friable and flaky silty sandstone, mostly covered. Fresh rock grayish-orange (10YR7/4)	12	205
21	Dark-gray to dark-brown carbonaceous shale with 2 lignite seams each 6 in. thick	5	193
20	Pale grayish-orange (10YR7/3) medium-bedded, medium- to fine-grained, fairly well-cemented sandstone forming rounded cliff	16	188
19	Pale brownish-gray (5YR5/2) carbonaceous shale, brown to black carbonaceous shale and lignite, and light-gray, friable, fine-grained sandstone in thin beds	7	172
18	Very light-gray (N8), medium-bedded, medium- to very fine-grained, fairly well-cemented sandstone, in rounded cliff	9	165
17	Yellowish-gray, massive, medium- to fine-grained sandstone forming vertical cliff	14	156
16	Gray to brown to black thin-bedded carbonaceous siltstone and shale, mostly covered	28	142
15	Cliff-making yellowish-gray crosslaminated medium- to fine-grained sandstone. Thickens to 30 ft 100 yards to the south	5	114
14	Coal (cut out by channel to the south)	3	109
13	Dusky-yellow (5Y6/4) siltstone (cut out to south)	1	106
12	Dark-brown to black carbonaceous shale, with 1-in. white clay layer 2 ft from top	6	105
11	Yellowish-gray silty clay with jasper septarian nodules at base and near top (cut out to south)	10	99
10	Dark-brown carbonaceous shale	2	89
9	Brownish to gray fine-grained siltstone and carbonaceous shale	13	87
8	Brownish to gray fine-grained siltstone with 1-in. ironstone nodule layer at top	20	74
7	Yellowish-gray, medium- to fine-grained sandstone	1	54
6	Brownish to gray fine-grained siltstone and carbonaceous shale	15	53
5	Gray thin-bedded sandstone and carbonaceous shale	22	38
4	Reddish-orange (10R6/6) massive, crosslaminated medium- to fine-grained sandstone with iron-cemented concretions	6	16
3	Dark-brown, weathering to gray, shaly lignite, with 0 to 4 in. of sandstone and pebble conglomerate at the top	1	10
2	Dark-brown to gray laminated and shaly, poorly cemented, fine-grained to very fine-grained sandstone	6	9
1	Pale-gray shaly siltstone with 6 in. of dark-brown to gray shaly lignite at top	3	3

Top of Point Lookout sandstone. Here a very pale-orange (10YR8/2), mottled, fairly well-cemented, nobby-weathering, medium- to fine-grained quartzose sandstone, 15 ft thick, lies above the main sandstone cliff.

This section contains 744 ft of siltstone, shale and coal, and 416 ft of sandstone, or nearly 36 percent sandstone.

Section 7 (pl 11) Lower Crevasse Canyon Formation (Dilco member and Dalton sandstone)

Measured southeastward from falls in Gallup sandstone on creek 1½ miles north of junction with north fork of Catron Creek, to top of ridge of Dalton sandstone. Tape measurements.

Unit No.	Description	Thickness in feet of unit	Thickness in feet from base
20	Upper Dalton sandstone, a pale yellowish-gray, medium-bedded (6 in. to 1 ft), fine-grained, friable sandstone with crosslaminations within the units. Limonite stains on flat bedding, top undulating. Composition about 80 percent subrounded quartz, 15 percent clay	30.0	399.5
19	Lower Dalton sandstone, a yellowish-orange, medium- to coarse-grained, massive sandstone, without crosslaminations. A few clay and ironstone concretionary and conglomerate lenses	45.0	369.5
18	Pale yellowish-gray medium- to thin-bedded sandstone and siltstone in alternating beds	35.0	324.5
17	Gray sandy siltstone	2.0	289.5
16	Bright coal	0.5	287.5
15	Gray carbonaceous siltstone with sandstone lenses and layers of gypsum	8.0	287.0
14	Gray thin-bedded siltstone	10.0	279.0
13	Pale yellowish-gray medium-grained friable sandstone	10.0	269.0
12	Gray carbonaceous siltstone with gypsum crystals near top	1.0	259.0
11	Pale yellowish-gray friable silty sandstone	15.0	258.0
10	Pale yellowish-orange, thin- to massive-bedded, crosslaminated, fine- to medium-grained, friable sandstone. Cavernous-weathering, cliff-forming. Iron-cemented layer at top	45.0	243.0
9	Pale yellowish-gray silty, friable sandstone, with gypsum crystals. Slope-forming	15.0	198.0
8	Gray silty clay and papery shale with gypsum crystals	17.0	183.0
7	Yellowish- to reddish-orange, thin-bedded, fine-grained sandstone	1.0	166.0
6	Yellowish-gray sandy siltstone	6.0	165.0
5	Cliff-making sandstone similar to No. 10	25.0	159.0
4	Coal	1.0	134.0
3	Alternating thin beds of gray sandy siltstone, carbonaceous shale and papery shale, with carbonaceous fragments	28.0	133.0
2	Gray papery shale with a few thin yellowish-gray fine-grained sandstone lenses	25.0	105.0
1	Upper Gallup sandstone. Cliff-forming, reddish to yellowish-orange, medium- to massive-bedded, medium- to coarse-grained (some grit and silt beds), crosslaminated quartzose sandstone, with some iron-cemented concretions	80.0	80.0

Base of waterfall and lowest unit exposed in the drainage of this branch of Catron Creek.

Section 8 (pl 11) Upper Crevasse Canyon Formation (Lower Gibson member)

Measured eastward from bed of creek, one-half mile north of junction with the north fork of Catron Creek, from point where creek crosses Dalton sandstone to top of ridge. Tape measurements.

Unit No.	Description	Thickness in feet of unit	Thickness in feet from base
82	Zone of burned coal and baked shale	10+	426.4
81	Sandy siltstone interbedded with papery gray shale	12.0	416.4
80	Pale yellowish-orange (10YR8/6) thin- to massive-bedded, crosslaminated, fine-grained, friable, sandstone with carbonaceous fragments and cavernous weathering	16.0	404.4
79	Coal	.5	388.4
78	Gray papery shale with carbonaceous fragments	1.3	387.9
77	Gray papery shale with carbonaceous fragments, interbedded with gray sandy siltstone, and with a 3-in. layer of ironstone nodules in the middle	8.0	386.6
76	Sandy shale	2.0	378.6
75	Coal	1.7	376.6
74	Gray papery shale with carbonaceous fragments	10.0	374.9
73	Coaly shale or shaly coal	1.0	364.9
72	Brown medium-grained sandstone, iron-cemented with coaly fragments	.5	363.9
71	Sandy siltstone	15.0	363.4
70	Brown iron-cemented sandstone	.8	348.4
69	Gray papery shale with carbonaceous fragments and coaly streaks	3.0	347.6
68	Yellowish-orange thin-bedded fine-grained sandstone	2.0	344.6
67	Gray papery shale with carbonaceous fragments	2.0	342.6
66	Yellowish-orange thin-bedded fine-grained sandstone	2.0	340.6
65	Gray sandy siltstone	2.0	338.6
64	Yellowish-orange thin-bedded fine-grained sandstone	1.5	336.6
63	Gray papery shale with carbonaceous fragments	3.0	335.1
62	Carbonaceous and bony or coaly shale	1.0	332.1
61	Gray sandy siltstone	2.0	331.1
60	Yellowish-orange thin-bedded fine-grained sandstone	3.0	329.1
59	Gray papery shale with carbonaceous fragments	2.0	326.1
58	Yellowish-orange thin-bedded fine-grained sandstone	.7	324.1
57	Gray papery shale with carbonaceous fragments	8.0	323.4
56	Pale yellowish-orange (10YR8/6) thin- to massive-bedded, crosslaminated, fine-grained, friable sandstone with carbonaceous fragments and cavernous weathering	16.0	315.4
55	Gray carbonaceous shale, more coaly towards top	.8	299.4
54	Thin-bedded sandstone with silty coaly lenses	2.0	298.6
53	Medium-gray silty claystone	4.0	296.6
52	Brown iron-cemented fine-grained sandstone	1.5	292.6
51	Gray silty shale	7.0	291.1
50	Dark gray carbonaceous shale	.5	284.1
49	Coal	1.0	283.6
48	Dark-gray carbonaceous shale	4.0	282.6
47	Gray sandy siltstone	6.0	278.6
46	Cliff-forming pale grayish-yellow, thin- to massive-bedded, crosslaminated, cavernous-weathering, fine-grained sandstone with carbonaceous flakes	40.0	272.6
45	Coaly shale	.7	232.6
44	Reddish-brown siltstone with carbonaceous fragments and some sandy lenses and ironstone concretions	20.0	231.9
43	Coal	3.5	211.9
42	Reddish-brown siltstone similar to No. 44	18.0	208.4
41	Yellowish-brown spheroidal-weathering, fine-grained, massive, iron-cemented sandstone	1.5	190.4
40	Reddish-brown siltstone similar to No. 44	34.0	188.9
39	Clayey coal or bone	1.5	154.9
38	Yellowish-gray sandy siltstone	6.5	153.4
37	Yellowish-gray crosslaminated, thin- to thick-bedded, friable, fine-grained, clay-cemented, cavernous-weathering sandstone	7.0	146.9

Unit No.	Description	Thickness in feet of unit	Thickness in feet from base
36	Reddish-brown to yellowish-gray (5Y7/2) weathering, poorly bedded siltstone, with some layers of ironstone concretions	30.0	139.9
35	Similar to No. 36 above, but more weather-resistant and containing numerous carbonaceous fragments, twigs, etc.	1.0	109.9
34	Similar to No. 36 above	14.0	108.9
33	Coal	1.5	94.9
32	Gray silty clay with carbonaceous fragments	2.0	93.4
31	Brown and gray papery shale, with carbonaceous fragments	10.0	91.4
30	Bony coal	.4	81.4
29	Pale-olive (10Y6/2) blocky-weathering claystone	10.0	81.0
28	Pale yellowish-gray thin-bedded, medium-grained sandstone	2.0	71.0
27	Yellowish-gray, iron-cemented, fine-grained, crosslaminated, friable sandstone, grades laterally into siltstone within 50 ft	12.0	69.0
26	Bright coal, with irregular top and bottom	.8	57.0
25	Pale yellowish-gray, thin-bedded siltstone with sandstone lenses and carbonaceous fragments, grades laterally into massive sandstone within 50 ft	5.0	56.2
24	Coaly shale	.3	51.2
23	Brownish-yellow, thin-bedded, sandy siltstone, with thin layers of sandstone and carbonaceous fragments	12.0	50.9
22	Dark reddish-brown iron-cemented, carbonaceous siltstone	1.0	38.9
21	Bright coal	1.0	37.9
20	Gray thin-bedded sandstone, sandy siltstone and siltstone	10.0	36.9
19	Grayish-yellow fine-grained, friable sandstone with siltstone lenses, ironstone nodules and coaly material	4.0	26.9
18	Bright coal	.8	22.9
17	Carbonaceous shale	.3	22.1
16	Light-gray thin-bedded carbonaceous siltstone	1.0	21.8
15	Bright coal	.3	20.8
14	Carbonaceous shale	.5	20.5
13	Light-gray thin-bedded carbonaceous siltstone	4.0	20.0
12	Bright coal	.1	16.0
11	Light-gray thin-bedded carbonaceous siltstone	1.3	15.9
10	Bright coal	1.3	14.6
9	Medium-gray siltstone with carbonaceous fragments and sandy lenses	1.0	13.3
8	Gray papery shale	4.0	12.3
7	Pale-gray sandy siltstone with iron stains	.5	8.3
6	Medium-gray carbonaceous siltstone, some iron stain	1.0	7.8
5	Coaly shale	.3	6.8
4	Reddish-brown silty carbonaceous shale	2.5	6.5
3	Interbedded, thin-bedded yellowish-orange sandstone and carbonaceous shale	2.5	4.0
2	Yellowish-orange fine-grained sandstone, with carbonaceous fragments, clay and ferruginous cement	.7	1.5
1	Interbedded shale, siltstone and sandstone	.8	.8

Top of Dalton sandstone, which here is a pale yellowish-gray, medium-bedded (6 in. to 1 ft) with crosslaminations of these units, fine-grained, friable sandstone. Limonite stains on flat bedding. Top undulating. Composition about 80 percent subrounded quartz, 15 percent clay.

A LIST OF VEGETATION ON THE NAVAJO INDIAN RESERVATION OCCURRING IN MERRIAM'S LIFE ZONES

Compiled by DON W. CLARK, *Range Conservationist*

I. Hudsonian Zone (9,000-12,000 ft)

Trees

Common Name	Scientific Name
Fir, Alpine	Abies Lasiocarpa
Fir, Corkbark	Abies Lasiocarpa var. arizonica
Spruce, Engelmann	Picea engelmannii

Grasses

Bluegrass, Kentucky	Poa pratensis
Brome, nodding	Bromus anomalus
Wheatgrass, slender	Agropyron pauciflorum

Grasslike Plants

Rush	Juncus badius
Rush, wire	Juncus balticus
Sedge	Carex nebraskensis

Weeds

Bluebell	Mertensia franciscana
Coneflower	Rudbeckia laciniata
Daisy	Erigeron spp.
Geranium	Geranium spp.
Harebell	Campanula parryi
Marigold, marsh	Caltha leptosepala
Meadowrue	Thalictrum spp.
Violet	Viola canadensis

Shrubs

Elderberry	Sambucus spp.
Gooseberry	Grossularia spp.
Kinnikinnick	Arctostaphylos uva-ursi
Raspberry	Rubus strigosus

II. Canadian Zone (8,000-9,500 ft)

Trees

Aspen	Populus tremuloides
Douglas Fir	Pseudotsuga taxifolia var. glauca
Fir, white	Abies concolor
Juniper, ground	Juniperus communis
Pine, limber	Pinus flexilis
Spruce, blue	Picea pungens

Grasses

Bluegrass, Kentucky	Poa pratensis
Brome, nodding	Bromus anomalus
Manna grass	Glyceria elata
Mutton grass	Poa fendleriana
Needle grass, Columbia	Stipa columbiana
Redtop	Agrostis alba
Wheatgrass, slender	Agropyron pauciflorum

II. Canadian Zone (Cont'd)

Grasslike Plants

Common Name	Scientific Name
Rush	Juncus badius
Rush, wire	Juncus balticus
Sedge, Nebraska	Carex nebraskensis
Sedge, ovalhead	Carex festivella

Weeds

Common Name	Scientific Name
Avens	Geum spp.
Bluebell	Mertencia franciscana
Buttercup	Ranuculus flammula
Buttercup	Ranuculus inamoneus
Clover	Trifolium spp.
Coneflower	Rudbeckia laciniata
Columbine	Aquilegia caerulea
Columbine	Aquilegia elegantula
Coral-root	Corallorhiza maculata
Daisy	Erigeron spp.
Dandelion	Leontoda taraxacum
False-carrot	Pseudocymopterus montanus
Fernweed	Pedicularis spp.
Geranium	Geranium spp.
Groundsmoke	Gayophytum ramossimum
Groundsmoke	Gayophytum nuttallii
Harebell	Campanula parryi
Hawksbeard, tapertip	Crepis acuminata
Hawksweed	Hieracium fendleri
Horsemint, nettleleaf	Agastache pallidiflora
Iris	Iris missouriensis
Knotweed	Polygonum bistortoides
Marigold, marsh	Caltha leptosepala
Meadowrue	Thalictrum spp.
Mint	Mentha aruensis
Mule-ears	Wyethia spp.
Pennycress	Thlaspi spp.
Phlox	Phlox spp.
Pussytoes, rose	Antennaria rosulata
Rock-jasmine	Androsace septentrionalis
Sandwort	Arenaria fendleri
Sneezeweed, orange	Helenium hoopesii
Solomon-seal, false	Smilacina racemosa
Strawberry	Frageria ovalis
Violet	Viola canadensis
Willow-weed	Epilobium saximontanum
Wintergreen	Pyrola virens
Yarrow, western	Achillea lanulosa

Shrubs

Common Name	Scientific Name
Alder, mountain	Alnus tenuifolia
Ash, mountain	Sorbus dumosa
Brickle-bush	Coleosanthus umbellatus
Chokecherry	Prunus virginiana
Chokecherry, black western	Prunus melanocarpa
Current	Ribes spp.
Elderberry	Sambucus spp.
Gooseberry	Grossularia spp.
Honeysuckle	Lonicera spp.
Kinnikinnick	Arctostaphylos uva-ursi
Maple, mountain	Acer glabrum
Raspberry	Rubus strigosus
Rose	Rosa fendleria

II. Canadian Zone (Cont'd)

Common Name	Scientific Name
Snowberry	Symphoricarpos oreophilus
Thimbleberry	Rubus parviflorus
Willow	Salix spp.

III. Transition Zone (7,000-8,500 ft)

Trees

Juniper	Juniperus communis
Pine, ponderosa	Pinus ponderosa var. scopulorum

Grasses

Alkali grass	Puccinellia airoides
Barley, foxtail	Hordeum jubatum
Barley, meadow	Hordeum nodosum
Bluegrass, Kentucky	Poa pratensis
Dropseed, pine	Blepharoneuron tricholepsis
Fescue, Arizona	Festuca arizonica
Junegrass	Koeleria cristeta
Muhly, mountain	Muhlenbergia montana
Mutton grass	Poa fendleriana
Needlegrass, Columbia	Stipa columbiana
Needle and thread	Stipa comata
Redtop	Agrostis alba
Squirreltail	Sitanion hystrix
Wheatgrass, bearded	Agropyron subsecundum
Wheatgrass, western	Agropyron smithii

Grasslike Plants

Bulrush	Scirpus microcarpus
Rush	Juncus badius
Rush	Juncus tracyi
Rush, wire	Juncus balticus
Sedge	Carex eleocharis
Sedge	Carex interior
Sedge, dryland	Carex geophilia
Sedge, nebraska	Carex nebraskensis
Sedge, ovalhead	Carex festivella

Weeds

Alum-root	Heuchera rubescens
Antelope-horns	Asclepias capricornu
Aster	Aster spp.
Aster, golden	Chrysopsis villosa
Avens	Geum macrophyllum
Beardstongue	Pentstemon barbatus
Beardstongue	Pentstemon lentus
Beardstongue	Pentstemon rydbergii
Beardstongue	Pentstemon strictus
Bedstraw	Galium spp.
Beebalm	Monarda menthaefolia
Biscuit-root	Lomatium parryi
Bitterweed	Actinea lemmoni
Buckwheat, red-root	Eriogonum racemosum
Campion	Silene mengiesii
Carrot, false	Pseudocymopterus montanus
Cinquefoil	Potentilla spp.
Clover	Trifolium spp.
Clover, white sweet	Melilotus albus
Clover, yellow sweet	Melilotus officinalis
Cow-parsnip	Heracleum lanatum

III. Transition Zone (Cont'd)

Common Name	Scientific Name
Daisy	Erigeron spp.
Dandelion	Leontodon taraxacum
Dandelion, mountain	Agoseris glauca
Flax	Linum lewisii
Filia, scarlet	Gilia aggregata
Goldenrod	Solidago spp.
Groundsel, broom	Senecio spartioides
Groundsmoke	Gayophytum ramossimum
Groundsmoke	Gayophytum nuttallii
Hawksbeard, tapertip	Crepis acuminata
Hawksweed	Hieracium fendleri
Horsemint, nettleleaf	Agastache pallidiflora
Iris	Iris missouriensis
Knotweed	Polygonum histortoides
Larkspur	Delphinium nelsoni
Lupine	Lupinus argenteus
Lupine	Lupinus sitgreavesii
Milkvetch	Astragalus amphioxys
Milkvetch	Astragalus canovirens
Milkvetch	Astragalus confertiflorus
Milkvetch	Astragalus micromerius
Mint	Mentha arvensis
Mule-ears	Syethia spp.
Mustard	Draba reptans
Mustard	Draba spectabilis
Nettle	Urtica gracilis
Onion, nodding	Allium cernum
Paintbrush	Castilleja chromosa
Paintbrush	Castilleja linariaefolia
Pea, red and yellow	Lotus wrightii
Peavine	Lathyrus spp.
Pennycress	Thlaspi spp.
Phlox	Phlox cluteana
Phlox	Phlox diffusa
Pingue	Actinea richardsoni var. floribunda
Primosa, evening	Oenothera runcinata
Pussytoes, rose	Antennaria rosulata
Sandwort	Arenaria fendleri
Strawberry	Frageria ovalis
Thistle	Cirsium parryi
Thistle	Cirsium drummondii
Thistle	Cirsium undulatum
Wall-flower, western	Erysium capitatum
Wormwood	Artemisia dracunculoides
Yarrow, western	Achillea lanulosa

Shrubs

Common Name	Scientific Name
Alder, mountain	Alnus tenuifolia
Ash, mountain	Sorbus dumosa
Birch, water	Betula frontinalis
Bitterbrush	Purshia tridentata
Bower, virgins	Clematis lingusticifolia
Ceanothus, mountain	Ceanothus fendleri
Chokecherry	Prunus virginia
Chokecherry, black western	Prunus melanocarpa
Current	Ribes spp.
Holly, creeping	Berberis repens
Kinnikinnick	Arctostaphylos uva-ursi
Manzanita, green-leaf	Arctostaphylos patula
Maple, mountain	Acer glabrum
Mock-orange	Philadelphus microphyllus

III. Transition Zone (Cont'd)

Common Name	Scientific Name
Mountain-mahogany, curl-leaf	Cercocarpus ledifolius
Raspberry	Rubus strigosus
Rose	Rosa fendleri
Rose	Rosa manca
Rose	Rosa arizonica
Serviceberry	Amelanchier oreophila
Skunkbush	Rhus trilobata

IV. Upper Sonoran Zone (4,000-7,500 ft)

Trees

Cottonwood, Rio Grande	Populus wislizani
Hackberry	Celtis reticulata
Juniper, Rocky Mountain	Juniperus scopulorum
Juniper, Utah	Juniperus osteosperma
Locust, New Mexican	Robina neo-mexicana
Oak	Quercus spp.
Pine, piñon	Pinus edulis
Walnut, Arizona	Juglans major

Grasses

Alkali grass	Puccinellia parishii
Barley, foxtail	Hordeum jubatum
Bluestem, little	Andropogon scoparius
Bluestem, sand	Andropogon hallii
Bluestem, silver	Andropogon saccharoides
Blowout grass	Redfieldia flexuosa
Dropseed, giant	Sporobolus gigantea
Dropseed, sand	Sporobolus cryptandrus
Dropseed, spike	Sporobolus contractus
Dropseed, long-leaved	Sporobolus asper
Galleta	Hilaria jamesii
Grama, black	Bouteloua eriopoda
Grama, blue	Bouteloua gracilis
Grama, side-oats	Bouteloua curtipendula
June grass	Koeleria cristata
Manna grass	Glyceria stricta
Muhly, ring	Muhlenbergia torreyi
Muhly, spiny	Muhlenbergia pungens
Muhly, Thurber's	Muhlenbergia thurberi
Needle and thread	Stipa comata
Needlegrass, green	Stipa viridulis
Ricegrass	Oryzopsis bloomeri
Ricegrass, Indian	Oryzopsis hymenoides
Reedgrass, giant	Phragmites communis
Sacaton, alkali	Sporobolus airoides
Salt grass	Distichlis stricta
Sand-reed grass	Calamovilfa gigantea
Scratch grass	Muhlenbergia asperifolia
Slough grass	Bechmannia syzigachne
Squirreltail	Sitanion hystrix
Three-awn, poverty	Aristida divaricata
Three-own, red	Aristida longiseta
Tumble grass	Schedonnardus paniculatus
Vine-mesquite	Panicum abtusum
Wild-rye	Elymus salinus
Wild-rye, Canada	Elymus canadensis

IV. Upper Sonoran Zone (Cont'd)

Grasslike Plants

Common Name	Scientific Name
Arrow-grass	Triglochin concinna
Bulrush	Scirpus microcarpus
Cat-tail	Typha latifolia
Sedge	Carex specuicola
Sedge, dryland	Carex geophilia
Sedge, threadleaf	Carex filifolia

Weeds

Aster	Aster spp.
Aster, golden	Chrysopsis filiosa
Aster, golden	Chrysopsis villosa
Antelope horns	Asclepias capricornu
Beardstongue	Pentstemon angustifolius
Beardstongue	Pentstemon rydbergii
Beardstongue	Pentstemon strictus
Bedstraw	Galium spp.
Bitterweed	Actinea lemmoni
Bladder-pod	Lesquerella intermedia
Bladder-pod	Lesquerella rectipes
Blanket-flower	Gaillardia pinnatifida
Broom-rape	Orobanche spp.
Buckwheat, red-root	Eriogorum racemosum
Campion	Silene menziesii
Canaigre or Sanddock	Rumex hymenosepalus
Carrot, false	Pseudocymopterus montanus
Chimaya	Cymopterus fendleri
Clover, white sweet	Melilotus albus
Clover, yellow sweet	Melilotus officinalis
Cryptantha	Cryptantha abata
Cryptantha	Cryptantha jamesii
Daisy	Erigeron spp.
Death-camas	Zygadenus paniculatus
Desert-plume	Stanleya albescens
Desert-plume	Stanleya elata
Flax	Linum aristatum
Flax	Linum lewisii
Gilia, scarlet	Gilia aggregata
Goldenrod	Solidago spp.
Gromwell	Lithospermum incisum
Groundsel	Senecio longilobus
Gumweed	Grindelia squarrosa
Hawksbeard	Crepis glauca
Hawksbeard	Crepis accidentalis
Hoarhound	Marrubium vulgare
Hymenopappus pauciflorus	Hymenopappus
Jimpson-weed	Datura meteloides
Larkspur	Delphinium nelsoni
Lettuce, wild	Lactuca pulchella
Loco, purple	Astragalus mollissimus
Loco, white	Astragalus lambertii
Lupine	Lupinus cutteri
Mallow, false	Malvastrum spp.
Mallow, globe	Sphaeralcea parvifolia
Mariposa-lily	Calochortus gunnisonii
Mariposa-lily	Calochortus nuttallii
Milkvetch	Astragalus amphioxys
Milkvetch	Astragalus canovirens
Milkvetch	Astragalus confertiflorus
Milkvetch	Astragalus lonchocarpus
Milkvetch	Astragalus micromerius

IV. Upper Sonoran Zone (Cont'd)

Common Name	Scientific Name
Milkvetch	Astragalus zionis
Milkweed	Asclepias cutleri
Milkweed, whorled	Asclepias galioides
Monkey-flower	Mimulus spp.
Mullein	Verbascum thapsus
Mustard	Draba reptans
Mustard, western tansy	Sophia incisa
Nettle, bull	Solanum elaeagnifolium
Nightshade	Solanum trifolium
Onion	Allium spp.
Paintbrush, Indian	Castilleja chromosa
Paintbrush, Indian	Castilleja linariaefolia
Pea, red and yellow	Lotus wrightii
Peavine	Lathyrus spp.
Phlox	Phlox diffusa
Phlox	Phlox stansburyi
Plantain, buckhorn	Plantago lanceolata
Plantain, common	Plantago major
Potato, wild	Solanum jamesii
Prairie-clover	Petalostemum candidum
Primrose, evening	Oenothera caespitosa
Primrose, evening	Oenothera lavandulaefolia
Rock-cress	Arabis spp.
Spiderwort	Tradenscantia occidentalis
Sunflower	Helianthus anomalus
Sunflower	Helianthus nuttallii
Sunflower, wood	Helianthella microcephala
Thistle	Circium bipinnatum
Thistle	Circium drummondii
Thistle	Circium nidulum
Thistle	Circium parryi
Thistle	Circium pulchellum
Thistle	Circium undulatum
Verbena, sand	Abronia elliptica
Verbena, sand	Abronia frogans
Verbena, sand	Abronia pumila
Vervain	Verbena spp.
Wafer-parsnip	Cymopterus purpurascens
White-evening-primrose	Anogra spp.
Wormwood	Artemisia dracunculoides

Shrubs

Common Name	Scientific Name
Apache-plume	Fallugia paradoxa
Aplopappus	Aplopappus spp.
Ash, flowering	Fraxinus cuspidata
Baccharis	Baccharis spp.
Bitterbrush	Purshia tridentata
Blackbrush	Colerogyne ramosissima
Buckthorn	Rhamnus spp.
Buckwheat, scrubby	Eriogonum leptophyllum
Buckwheat, Wright's	Eriogonum wrightii
Buffalo-berry	Shepherdia rotundifolia
Bushmint	Poliomintha incana
Camel-thorn	Alhagi camelorum
Chamise	Atriplex canescens
Clematis	Clematis spp.
Cliff-fendler's bush	Fendlera rupicola
Cliffrose	Cowania stansburiana
Cactus, hedgehog	Echinocerus spp.
Cactus, cholla	Opuntia spp.
Cactus, prickly-pear	Opuntia engelmannii

IV. Upper Sonoran Zone (Cont'd)

Common Name	Scientific Name
Cactus, prickly-pear	Opuntia hystricina
Cactus, prickly-pear	Opunta polyacantha
Cactus, prickly-pear	Opuntia whipplei
Grape, wild	Vitis arizonica
Greasewood	Sarcobatus vermiculatus
Gumbush	Vanclevea stylosa
Holly-grape	Berberis fremontii
Hop-sage	Grayia spinosa
Horsebrush	Tetradymia canescens
Manzanita, greenleaf	Arctostaphylos patula
Mock-orange	Philadelphus microphyllus
Mountain-mahogany, curl-leaf	Cercocarpus ledifolia
Mountain-mahogany, true	Cercocarpus montanus
Mormon-tea	Ephedra cutleri
Mormon-tea	Ephedra torreyana
Oak, Gambel's	Quercus gambelii
Oak, scrub, live	Quercus turbinella
Parryella	Parryella rotundata
Rabbitbrush	Chrysothamnus nauseosus var. bigelovii
Rabbitbrush	Chrysothamnus nauseosus var. latisquameus
Rabbitbrush	Chrysothamnus nauseosus var. gnaphalodes
Red-bud	Cercis occidentalis
Sage	Salvia spp.
Sagebrush, bud	Artemisia spinescens
Sagebrush, big	Artemisia tridentata
Sagebrush, fringed	Artemisia frigida
Sagebrush, sand	Artemisia filifolia
Sagebrush, small	Artemisia nova
Serviceberry	Amelanchier oreophila
Shadscale	Atriplex confertifolia
Shadscale	Atriplex argentea
Shadscale	Atriplex sabulosa
Skunkbush	Rhus trilobata
Snakeweed	Gutierrezia sarothrae
Snowberry	Symphoricarpus palmeri
Spanish-dagger	Yucca baccata
Wild-olive	Forestiera neo-mexicana
Winterfat	Eurotia lanata
Wolfberry	Lycium pallidum
Yellowbrush	Chrysothamnus pulchellus
Yellowbrush	Chrysothamnus viscidiflorus
Yucca	Yucca angustissima
Yucca	Yucca harrimaniae
Yucca	Yucca navajoa

ANNUAL PLANTS

Common Name	Scientific Name	Life Zone
Bristlegrass, green	Setaria viridis	Upper Sonoran
Buffalograss, false	Munroa squarrosa	Upper Sonoran
Chess	Bromus arvensis	Transition
Chess, Japanese	Bromus japanicus	Transition
Cheatgrass	Bromus tectorum	Upper Sonoran
Dropseed, six-weeks	Sporobolus microspermus	Upper Sonoran
Fescus, six-weeks	Festuca octiflora	Upper Sonoran
Grama, six-weeks	Bouteloua barbata	Upper Sonoran

Weeds

Common Name	Scientific Name	Life Zone
Beeweed, Rocky Mtn.	Cleome serrulata	Upper Sonoran
Beeweed, yellow	Cleome lutea	Upper Sonoran
Caterpillar-weed	Phacelia demissa	Upper Sonoran
Cocklebur	Xanthium commune	Upper Sonoran
Croton	Croton texansis	Upper Sonoran
Cryptantha	Cryptantha pterocarpa	Upper Sonoran
Filaree	Erodium cicutarium	Upper Sonoran
Indian-wheat	Plantago purshii	Upper Sonoran
Knotweed	Polygonum pennsylvanicum	Upper Sonoran
Lamb's-quarter	Chenopodium album	Upper Sonoran
Paintbrush	Castilleja exilis	Upper Sonoran
Peppergrass	Lepidium spp.	Upper Sonoran
Powder-horn	Cerastium texanum	Transition
Red-root	Amaranthus cruentus	Upper Sonoran
Seepweed	Suaedo depressa	Upper Sonoran
Shepherd's purse	Bursa-bursa pastoris	Upper Sonoran
Spectacle-pod	Dithyrea wislizeni	Upper Sonoran
Stickseed	Lappula occidentalis	Upper Sonoran
Sunflower	Helianthus annuus	Upper Sonoran
Thistle, Russian	Salsola kali var. tenuifolia	Upper Sonoran

INTRODUCED PLANTS

Grasses

COMMON NAME	SCIENTIFIC NAME	INTRODUCED FROM	LIFE ZONE
Brome, smooth	Bromus inermis	Russia	Canadian
Bristlegrass, green	Setaria viridis	Europe	Upper Sonoran
Cheatgrass	Bromus tectorum	Eurasia	Upper Sonoran
Chess	Bromus arvensis	Eurasia	Upper Sonoran
Chess, Japanese	Bromus japanicus	Eurasia	Transition
Quackgrass	Agropyron repens	Eurasia	Upper Sonoran
Stinkgrass	Eragrostis cilianensis	Europe	Upper Sonoran
Timothy	Phleum pratense	Eurasia	Canadian
Wheatgrass, crested	Agropyron cristatum	Russia	Canadian

Weeds

COMMON NAME	SCIENTIFIC NAME	INTRODUCED FROM	LIFE ZONE
Knotweed	Polygonum amphilium	Eurasia	Upper Sonoran
Knotweed	Polygonum convolvulus	Eurasia	Upper Sonoran
Thistle, Russian	Salsola kali var. tenuifolia	Eurasia	Upper Sonoran

Shrubs

COMMON NAME	SCIENTIFIC NAME	INTRODUCED FROM	LIFE ZONE
Tamarisk	Tamarix pen tandra	Eurasia	Upper Sonoran

GLOSSARY OF TECHNICAL TERMS
(exclusive of mineralogy)

AGGLOMERATE—Volcanic rock, composed of angular fragments, commonly found in volcanic conduits.

ALLUVIAL DEPOSIT—Rock material which has been transported by running water.

AMPHIBOLITE—A dark crystalline rock made up largely of hornblende.

ANAMORPHOSED ROCK—Made up of new minerals formed by metamorphism.

ANHEDRA—Mineral grains without crystal faces.

ANTICLINE—An arch in inclined layers of rock.

APHANITIC ROCK—Containing grains too small to be distinguished with the naked eye.

AQUIFER—A stratum or bed which transmits water.

ARENACEOUS—Sandy.

ARGILLACEOUS—Containing clay.

ARKOSE—A sandstone with mineral fragments, dominantly feldspar, derived from a granite.

BASALT—Dark, fine-grained lava.

BENTONITE—A rock consisting of clay minerals, and usually characterized by the property of swelling when wet.

BRECCIA—A rock made up of angular fragments.

BUCHITE—Vitrified sandstone.

CALCAREOUS—Containing calcium carbonate.

CALDERA—A large volcanic depression, more or less circular in form, the diameter of which is many times greater than that of the included vent or vents.

CHERT—A dense, hard rock composed of aphanitic silica.

CLASTIC—Formed from fragments of other rocks or minerals.

COGNATE XENOLITHS—Inclusions of a type of rock similar to that which encloses them.

CONCRETION—A rounded mass of rock formed in place by the cementation of particles.

CONGLOMERATE—A rock made up largely of pebbles or cobbles.

CONTOUR—A line on a map which connects all points of equal elevation on a given surface, or layer of rock.

CROSSLAMINATIONS—Thin parting planes within a bed or stratum inclined to the plane of the bed.

CUESTA—An asymmetrical ridge, resulting from the erosion of a gently-dipping resistant stratum, commonly a sandstone.

DELTA—Sedimentary deposit at the mouth of a river or stream, where it enters a lake or sea.

DETRITUS—Any loose material that results directly from rock disintegration.

DIATREME—A volcanic vent drilled through the enclosing rocks by the explosive energy of gas-charged magma.

DIKE—A sheetlike mass of igneous rock which fills a fracture, and cuts across older structures.

DIORITE—A coarse-grained igneous rock largely composed of hornblende and plagioclase.

DIP—The degree of the inclination of a rock stratum from the horizontal.

ECLOGITE—A more or less schistose metamorphic rock, made up of light-green pyroxene, actinolite, and garnet.

EOLIAN—Sediment deposited by the wind.

EPEIROGENIC—Very slow up or down movements of large parts of the earth's crust.

EROSION—The general wearing away of the land by running water, wind, and other agencies.

EUHEDRA—Mineral grains with well-developed crystal faces.

FAULT—A fracture in the rocks, along which appreciable relative movement has taken place.

FELDSPATHIC—Containing much feldspar.

FERRUGINOUS—Containing iron oxide.

FISSILE—Splitting into thin flakes.

FLUVIATILE—Pertaining to streams.

FORESET BEDS—Inclined layers of sediment, forming the sloping front of deltas and bars.

FORMATION—A set of strata having common characteristics that can be mapped as a unit.

FUSULINIDS—Minute, spindle-shaped, unicellular animals.

GABBRO—A coarse-grained, dark-colored, igneous rock containing plagioclase and clinopyroxene.

GNEISSIC ROCK—A metamorphic rock which exhibits layers of different color or texture.

GOUGE—Rock flour, formed mechanically by movement along faults.

GPD—Gallons per day.

GPM—Gallons per minute.

HETEROMORPH—Rock having the same chemical composition as another rock, but differing in mineral composition.

HOGBACK—A narrow ridge composed of a resistant, steeply dipping stratum of rock, usually sandstone.

IGNEOUS ROCK—Solidified from a molten state.

INTERMITTENT STREAM—One which flows part of the year only.

ISOCLINAL FOLDS—Layered rocks folded so tightly that the flanks of the folds have identical parallel orientation.

JOINT—A fracture in rock, without appreciable displacement of the two sides.

KIMBERLITE—A brecciated, dark, igneous rock, composed of fresh or altered pyroxenes, olivine, and other minerals.

LACCOLITH—An igneous mass intruded between layers of sedimentary rock as a lens.

LACUSTRINE—Pertaining to lakes, especially to sediments deposited therein.

LAPILLI—Walnut-sized fragments of volcanic rock erupted from volcanoes.

LEUCITITE—An igneous rock containing leucite, a potash-rich silicate mineral.

LIESEGANG RINGS—Concentric bands of iron or manganese oxide.

LIGNITIC—Containing carbonized woody material.

LITHOLOGIC—Pertaining to rock character.

MAGMA—Molten rock below the surface of the earth.

MATRIX—Material interstitial between the grains of a rock.

METARHYOLITE—Metamorphosed rhyolite (see rhyolite).

MICROMHOS—A measure of electrical conductivity.

MINERAL—A naturally occurring, inorganic, generally crystalline substance, having more or less definite physical characteristics and chemical composition.

MINETTE—A dark igneous rock composed of biotite, potash feldspar, and other minerals.

MONOCLINE—Strata dipping in one direction.

MORPHOLOGICAL—Referring to the shape of the land surface.

NECK—Lava-filled conduit of an extinct and eroded volcano.

NIVATION—The process of erosion by snowfields.

NORITE—A dark igneous rock similar to gabbro, except that the pyroxene is orthorhombic.

OUTCROP—That part of the bedrock exposed at the surface without appreciable soil or alluvial cover.

PEDIMENT—A sloping plain, caused by erosion, lying at the foot of steeper mountain slopes.

PENEPLAIN—A surface of slight relief produced by long continued erosion; also such a surface after it has been uplifted and dissected.

PERENNIAL STREAM—One which flows throughout the year.

PETRIFIED—Changed into stone.

PLUG—Core of an extinct and eroded volcano.

POIKILOBLASTIC CRYSTAL—A rather large grain, in a metamorphic rock, that encloses numerous grains of other crystals.

PORPHYRITIC—The texture of an igneous rock which contains large crystals in a finer-grained groundmass.

PPM—Parts per million.

QUARTZITE—A sandstone cemented by silica, or recrystallized by metamorphism.

RESIDUAL SOIL—Soil formed in place.

RHYOLITE—A light-colored siliceous lava.

ROCK—A part of the crust of the earth, made up of one or more minerals.

SCHIST—A finely foliated metamorphic rock.

SECONDARY MINERAL—A mineral deposited or formed after the original rock has been consolidated.

SEDIMENT—A rock composed of rock or mineral particles which have been deposited by water, wind, or ice.

SEPTARIAN NODULES—Nodules split by an irregular polygonal system of internal cracks.

SILICIFIED—Partly or wholly replaced by silica.

SLICKENSIDE—The polished and grooved surfaces produced by fault movement.

SPECIFIC CONDUCTANCE—Electrical conductivity per unit length (measured in micromhos).

STRATH—A broad valley with a planated floor.

STRATIGRAPHIC—Pertaining to the strata, or the science or study of the strata.

STRATUM—(plural, strata) A layer or bed of rock.

STRIKE—Direction of trend of a horizontal line on an inclined stratum.

SUBHEDRAL—With poorly developed crystal faces.

SUBSEQUENT VALLEY—A valley carved in soft rocks between dipping, more resistant layers of rock.

SYNCLINE—A downfold (opposite of anticline) of stratified rock.

SYSTEM—Rocks belonging to a geologic period of time.

TALUS—Accumulated rock fragments at the foot of a cliff or slope.

THINSECTION—A slice of rock, 0.002 inch thick, prepared for microscopic examination.

TRACHYBASALT—Dark lava resembling basalt, but containing more potash.

TUFA—Cellular deposits of mineral springs, usually calcareous or siliceous.

TUFF—Consolidated volcanic ash.

UNCONFORMITY—An erosional break in the continuity of sedimentation.

VESICULAR—Containing cavities (vesicles) resulting from gas bubbles during cooling of lava.

VITRIFIED—Changed to glass.

VUGS—Open cavities in rock, usually lined with crystals.

XENOLITH—A fragment of a different type of rock enclosed in an igneous rock.

NAVAJO WORDS FOR GEOLOGIC TERMS

The Navajo language reflects an interest in, and comprehension of, many geologic features. Some of the terms are as precise as technical geologic terms. For instance, the size range of sedimentary rock components is spanned in the terms:

tse' tso	(boulder)
tse'' a' ma' zi	(large pebble: small boulders, usually round)
tse'' a' wo' zi	(pebble: usually refers to quartz or flint, water-shaped or worn rocks)
tse' za'i'	(gravel)
se'i'	(sand)
hashtł'ish	(mud)

Numerous compounds of the term "tse" (rock) are used to build sedimentary rock terms, with emphasis frequently upon the color:

noolyi'ni'	(obsidian)
tse' chi''ii	(red stone: garnet, sandstone)
nił	(axe stone, quartz or hard rock used in making stone implements or tools)
tse' łichi'i'ii	(red-white stone: jasper, agate)
tse' sǫ'	(rock-star: glasslike, transparent or opaque glasslike rocks)
tse' di'ne'e sa'	(growing stone: bentonite?)
tse' diłdǫ' ii	(exploding stone: limestone)
tł'e' e' ł beeikał	(flint)
tse' łigaai'	(gypsum)
tse' łitso	(ochre)
tse' je'i	(amber: dark hard stone)
tse' n daaz	(heavy-stone: meteorite, iron-bearing stone)

Other sediments or sedimentary rocks are:

bis	(adobe clay or any clay bank)
dleesh	(white clay)
deeshchii'	(red clay)
łeetso	(yellow clay or sulfur, now widely applied to carnotite or other uranium ores)
bis doott'izh	(blue clay)
łeezh łizhini	(dark or black soil, or mountain soil)
łeeya'a'n	(alkali, alkali earth)

Both coal (łeejin) and coal croppings (tse' nii'a'i), as well as indications of oil (łeełiyini) are listed. Malpais or lava is tse' zhinii (black rock).

Mineral terms are not usually differentiated from rocks, but include the following:

tse' dootł'izh	(specular hematite)
tse' ko'	(mica, biotite)
tse' dootł'izhi	(peridot or olivine)
tse' gha'di'nidinii	(clear rock crystal)
dootł'izhii	(turquoise)
tse' na'sta'nii	(petrified wood, rock log)
tse' łichi''ii	(garnet)

Numerous geographic terms are used; a sampling of the more common ones are:

ni'haldzis	(bowl, basin without drainage leading off)
te'e'h	(valley)
cha'shk'eh	(arroyo, gulch)
bikooh	(deep arroyo or any canyon)
tse' kooh	(rock canyon)
deesk'id	(hill)
dah nask'id	(knob)
dah a'ts'os	(peak)
dził	(mountain, as in dziłditł'ooi)
dadeesk'id	(series of hills or ridges)
tse' bił dadeez'a'	(rock bluffs)
bis bił dadeez'a'	(clay bluffs)
deez'a'	(promontory, as in Deza Bluffs)
dził bigeez	(mountain pass or gap)
dził tsi'i'n	(mountain base)
dził ta't'ah	(bench, shelf on side of mountain)

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