Geology and Uranium Deposits of the Laguna District, New Mexico

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A study of the Jackpile mine and other uranium deposits and their relations to regional stratigraphy, structure, and tectonics

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ABSTRACT

The Laguna district, about 50 miles west of Albuquerque, N. Mex., forms the southeast end of the Southern San Juan Basin mineral belt, a west- to northwest-trending zone of uranium deposits associated mainly with stratigraphic and tectonic structural features of Jurassic age. The belt roughly conforms with the north margin of the Jurassic Mogollon Highland. Within the district are the Jackpile uranium deposit, containing many million tons of ore, and several other large uranium deposits; all the deposits are in the Jackpile sandstone, the uppermost unit in the Morrison Formation of Jurassic age. Several small deposits are in sandstone strata of the lower part of the Morrison Formation, in the limestone of the Todilto Formation, or in the Entrada Sandstone, also of Jurassic age. Only the Jackpile mine, however, produced significant amounts of uranium ore prior to 1962. Between about 1956 and 1960 it was the largest single producer of uranium in the United States, and possibly in the world.

Sedimentary rocks exposed in the Laguna district range in age from Triassic to Late Cretaceous. From oldest to youngest these are the Chinle Formation of Late Triassic age; the Entrada Sandstone, Todilto Formation, Summerville Formation, Bluff Sandstone, and Morrison Formation of Late Jurassic age; and the Dakota Sandstone and the intertonguing strata of the Mancos Shale and Mesaverde Group of Cretaceous age. The exposed column totals about 3,800 feet in thickness, of which about 1,300 feet is Jurassic strata. Before deep erosion began in Tertiary time, the Jurassic rocks were buried by possibly a mile of Cretaceous rocks and an additional unknown thickness of lower Tertiary rocks.

In Triassic time the bentonitic mudstone beds of the Petrified Forest Member of the Chinle Formation accumulated on a broad alluvial flood plain to an aggregate thickness of more than 1,000 feet. In part, these sediments represent altered and redistributed volcanic ash. Sandstone and conglomerate of the Correo Sandstone Member of the Chinle, generally less than 100 feet thick, were then deposited by streams that flowed from the southeast.

After a period of erosion, the Entrada Sandstone accumulated in Late Jurassic time. This formation is divisible into three distinct units: a discontinuous basal unit of sandstone and sparse conglomerate locally more than 30 feet thick; a medial unit of interbedded mudstone, siltstone, and sandstone 35–85 feet thick; and an upper unit of sandstone 80 to nearly 200 feet thick. Sands of the two sandstone units evidently were transported by streams flowing northward from the Jurassic Mogollon Highland, but later the sands were reworked by persistent north winds to form eolian deposits having dominantly south-dipping crossbedding. Such winds possibly blew onshore from a large body of water to the north. With the southward advance of this sea between the two stages of sand deposition, the mud, silt, and sand of the medial unit accumulated.

The upper part of the upper sandstone unit was altered from red to white, possibly shortly after deposition. This alteration was accompanied by the breaking down of detrital opaque minerals and the leaching of iron, vanadium, possibly uranium, and several other elements.

The Todilto Formation then accumulated in a shallow but extensive lake, or possibly in a sea embayment. Widespread deposits of laminated to massive limestone as much as 35 feet thick accumulated first; then lenticular deposits of gypsum as much as 60 feet thick were precipitated locally.

The Summerville Formation is characterized by contrasting poorly sorted matrix-rich sandstone and well-sorted sandstone. The matrix-rich sands may have accumulated from sheet washes and mudflows on a subaerial mudflat. These sands may have been reworked during successive shallow inundations, during which the fine-grained matrix material was winnowed out and the sorting greatly improved.

The Bluff Sandstone, which ranges from less than 200 to nearly 400 feet in thickness, was laid down during a time when wind action was increasing. Its lower part, characterized by alternating horizontally stratified and cross-stratified units, probably represents combined alluvial and eolian sedimentation briefly interrupted by shallow marine inundations. Its upper part, characterized by very large scale cross-stratification that dips consistently and steeply eastward, is dominantly eolian.

The Morrison Formation sedimentation began when the processes changed abruptly from eolian to dominantly alluvial. This formation, which is locally 600 feet thick, is divisible into four units: in ascending order, the Recapture, Westwater Canyon and Brushy Basin Members, and the Jackpile sandstone of economic usage. The Recapture Member, which is generally less than 100 feet thick, is composed of thinly interstratified varicolored mudstone, siltstone, sandstone, and limestone that were deposited in slow-moving streams and scattered lakes on a broad alluvial plain. The Westwater Canyon Member, which is locally more than 100 feet thick, is composed of very pale orange fine- to coarse-grained cross-stratified arkosic sandstone of alluvial origin; it represents a major rejuvenation of the source area to the southwest. The Brushy Basin Member is an extensive unit as much as 300 feet thick; it is composed of grayish-green bentonitic mudstone, in part representing altered and redistributed volcanic ash, and subordinate thin units of arkosic sandstone. These materials probably accumulated on a broad gradually subsiding alluvial flood plain. The Jackpile sandstone is a northeast-trending body of nearly white fine- to medium-grained cross-stratified sandstone as much as 13 miles wide, at least 33 miles long, and locally more than 200 feet thick. It was deposited by a system of streams that flowed northeastward

along a syncline that broadened and deepened during sedimentation.

Morrison sedimentation was followed by a long period of erosion and weathering. During this period the region was tilted gently northward, and an extensive erosion surface formed that truncates successively older strata southward. Sandstones directly below this surface were weathered and kaolinized.

Accumulation of fluvial, paludal, and other near-shore deposits of the Dakota Sandstone preceded the advance of the Mancos sea in Late Cretaceous time. Intertonguing strata of the Mancos Shale and Mesaverde Group then accumulated during successive transgressions and regressions of this sea. Probably more than 5,000 feet of Cretaceous strata was laid down, and on this an unknown thickness of early Tertiary sediments was deposited.

Exposed igenous rocks, which are of late Tertiary to Quaternary age, consist of basalt plugs, a succession of basalt flows that cap eroded pediments at several levels above the lowest level of drainage, and pyroclastic deposits of acidic to intermediate composition that are interstratified with the oldest flows. These rocks constitute part of the Mount Taylor volcanic field, most of which lies northwest of the district. In addition, diabase sills and dikes, apparently unrelated to the volcanic field, are exposed in the central and southern parts of the district. Except for the volcanics of the Morrison Formation, the diabase is probably the oldest igneous rock of the district; sills and dikes have locally intruded and metamorphosed uranium deposits and have apparently pyritized much of the Bluff and Entrada Sandstones.

The district is in the southeast corner of the San Juan Basin of the Colorado Plateau. Cretaceous strata near the major uranium deposits dip gently northwestward into the basin. The north-trending San Ignacio faulted monocline marks the boundary between the Colorado Plateau and the Rio Grande depression to the east. Three general periods of tectonic activity are recognized: (1) gentle folding in Jurassic time, (2) regional tilting and gentle folding in early Tertiary time, and (3) regional joining, faulting, and igneous activity in later Tertiary and possibly Quarternary time.

The Jurassic deformation produced two sets of low-amplitude folds, the major set trending east to northeast, the other, north-northwest. This folding was accompanied by lateral flowage of unconsolidated limestone of the Todilto Formation into the synclines, and the flowage, in turn, produced the variety of intraformational folds and faults that characterize that unit and resulted in the thickening of limestone in the synclines. Folding was also accompanied by slumping and internal faulting of unconsolidated clastic sediments and by the formation of hundreds of peculiar cylindrical subsidence features called sandstone pipes. Folding also markedly influenced Jurassic sedimentation, particularly of the Jackpile sandstone.

Early Tertiary deformation produced the major Cenozoic folds of the region. The San Juan Basin acquired approximately its present configuration; beds in the northern part of the Laguna district were tilted gently northward and westward. The north-trending Madera anticline and Arch Mesa syncline, as well as several small domes and basins, formed in the eastern part of the district.

The third and youngest deformation probably reached a climax during rapid subsidence and sedimentation in the nearby Rio Grande depression in late Tertiary time. In the district, this deformation produced the north-trending normal faults, most of the joints in the sedimentary rocks, and possibly the San Ignacio faulted monocline. These structural features probably formed by regional east-west elongation. The third deformation was accompanied by the emplacement of an interconnecting system of diabase sills and dikes, for dikes occupy joints characteristic of the fracture system, and sills are cut by joints and faults of the same fracture system.

Pedimentation, uplift, and dissection characterize the late Cenozoic geomorphic history of the region. In Pliocene or possibly early Pleistocene time, an erosion surface of low relief (Ortiz surface) formed over the entire region. This erosion surface was then uplifted and deeply eroded, and successively lower and less extensive pediments were formed.

Uranium deposits in the Laguna district are in the east end of the Southern San Juan Basin mineral belt. This belt is parallel to several controlling and definitive geologic features of Jurassic age but is widely divergent from the major structural features of Tertiary age. Within the district most deposits are concentrated in elongate groups and apparently are controlled by Jurassic tectonic features and by sedimentary trends in the host rocks.

The large uranium deposits in the Jackpile sandstone are composed of one or more semitabular ore layers. In plan view they range from nearly equant to strongly elongate. Viewed in section the layers are wholly within the host sandstone; only locally do they border directly on mudstone strata, diastems, or formational contacts. The Jackpile deposit, the largest in the district, is nearly 6,000 feet long and averages about 2,000 feet in width; individual ore layers rarely exceed 15 feet in thickness, but several layers may aggregate 50 feet in thickness. A Jurassic fold of low amplitude may have influenced the localization of this deposit.

The Woodrow deposit, which was localized by a sandstone pipe, is small but contains high-grade ore. In the upper part of the deposit the ore is concentrated largely along the boundary ring faults; in the lower part the ore is lower grade and is distributed through the core of the pipe.

Deposits in the Entrada Sandstone and in limestone of the Todilto Formation in the Laguna district are small and rarely economic. Deposits in the limestone are localized in small intraformational folds of various shapes and generally follow the elongate form of the folds. Deposits in the sandstone are semitabular and semiconcordant and are typically wholly within the host sandstone. A group of deposits in the limestone and sandstone in the Sandy mine is localized along the crest and steep limb of a Jurassic fold.

Coffinite and uraninite, the chief ore minerals of the relatively unoxidized parts of deposits, are intimately mixed with carbonaceous matter, which is particularly abundant in deposits in the Morrison Formation. This mixture coats sand grains, locally impregnates the sandstone and embays its constituents, and accounts for the gray to black shades of Morrison ores. Other minerals associated with ore are vanadium clay (a fine-grained mixture of mica, probably roscoelite, montmorillonite, and chlorite), pyrite, and other sulfide minerals.

Available evidence suggests that the uraniferous carbonaceous matter originated from decaying vegetal matter. Infrared and chemical analyses of the material are indistinguishable from those of low-rank coal and are unlike those of petroleum or petroleumlike substances. In addition, infrared analysis has detected a salt of oxalic acid in carbonaceous matter from the Jackpile mine. Such salts, particularly calcium oxalate, are typically associated with plant remains.

Where oxidized, the ores contain various minerals of high-valent uranium and vanadium, which occupy pore spaces, line fractures, and coat old mine walls.

The ores of the Laguna district contain various amounts of uranium, vanadium, and many other elements that are more abundant in the ores than in the enclosing host rocks. Only rarely do the ores contain more than 1 percent uranium or vanadium; most of the ores average about 0.2 percent uranium and less vanadium. Uranium-vanadium ratios range from about 50 : 1 in the Woodrow deposit to 3 : 1 in the Jackpile and Windwhip deposits, 1 : 1 in the deposits at the Sandy mine, and 1 : 2 in the Crackpot deposit.

Ore textures indicate that replacement was a major process that accompanied mineralization. Uraniferous carbonaceous matter, vanadium clay, and sulfides strongly embay detrital quartz grains, preexisting clay, carbonate, and silica cements. The textures, however, do not reveal a consistent order of precipitation of the ore components.

The uranium deposits of the district may have formed in Jurassic time shortly after the accumulation of the host rocks, and perhaps when these rocks were exposed at the surface. At that time the broad east-trending Mogollon Highland existed a short distance to the south of the Southern San Juan Basin mineral belt and was probably the major source of sediments within the belt. Surface and ground waters flowing from the highland may have extracted uranium and vanadium from the rocks and transported them to the sites of deposition. Such waters could also have extracted soluble humic compounds from surficial or buried decaying plant debris. These substances could then have precipitated where the ground-water flow was impeded by the stratigraphic and tectonic structural features that are recognized in the mineral belt. Impedance and partial stagnation might have inhibited aeration and enhanced the reduction of sulfate by anaerobic bacteria. The resulting generally more reducing environment might have effected a reduction and precipitation of uranium. In addition, weak acidification of the ground water might also have caused the precipitation of alkali-soluble humic compounds, which in turn might have extracted more uranium from solution.

Probably no economic uranium deposits will be found in the Laguna district outside the known limits of the mineral belt. Favorable areas for prospecting in the Jackpile sandstone are to the west and northwest of the Jackpile and Paguate deposits. The Westwater Canyon Member of the Morrison, though at considerable depth in the Laguna district, should not be overlooked as a potential source of uranium. If and when the economics of deep drilling and mining permit, the entire area between the Laguna and Ambrosia Lake districts should be favorable prospecting ground.

Paleogeography provides the best guide to the discovery of uranium districts. Three geologic requirements should be satisfied. First, a broad upland area of weathering and erosion should border a shallow basin of continental sedimentation, preferably fluvial. Second, the climate of the region and the character of the rocks should be consistent with the development of ground waters chemically appropriate for the transportation of uranium. Third, the permeable sediments near the margins of the sedimentation basin should be characterized by thickness changes and perhaps by tectonic features that would impede the flow of ground water and enhance precipitation of the ore components.

INTRODUCTION

GEOGRAPHY

The Laguna uranium-mining district, for convenience defined as "the area described in this report," includes about 535 square miles on the east side of the Colorado Plateau; the center of the district is about 50 miles west of Albuquerque, N. Mex. (fig. 1). The district is crossed by U.S. Highway 66, a major east-west interstate highway, and has many graded roads and poor ungraded roads, which provide access to all parts of the district. The major geographic features, settlement, climate, and vegetation of most of the district were described by Hunt (1936, p. 37, 38).

The district is in mesa country that is typical of much of the Colorado Plateaus province. On its northwest side is Mesa Chivato, which is more than 8,000 feet in altitude, and on its east side is Mesa Gigante, which is more than 6,500 feet in altitude. Between these two

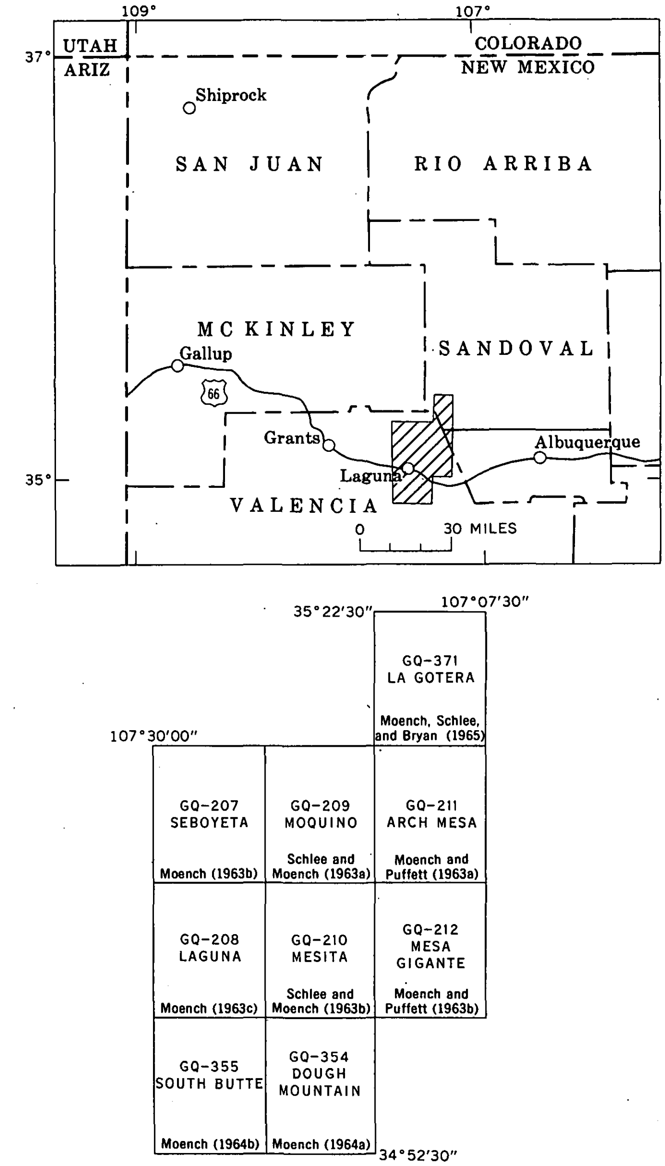

FIGURE. 1—Location of Laguna district, and index to geologic maps.

prominent mesas are several smaller mesas and benches capped by resistant strata that dip gently northward. The northeastern part of the district is characterized by low mesa-and-bench topography. Here, as well as farther south, the surface is pierced by several black, basaltic volcanic necks that rise abruptly as much as 1,000 feet above the surrounding country. Rocks in the central and northern parts of the district are typically drab, owing to the dominant gray and tan shades of the Cretaceous strata. To the south, various shades of red and yellow mark the colorful Jurassic and Triassic strata.

The Rio San Jose is the main stream in the district and, except a few brooks in the canyons on Mesa Chivato, is the only perennial stream. It drops from an altitude of about 5,900 feet on the west to less than 5,600 on the east and is entrenched 20 feet or more over most of its length. A few miles southeast of the district it joins the Rio Puerco, which in turn is tributary to the Rio Grande. Several arroyos join the Rio San Jose from the north and south, but ordinarily they contain water only after summer thunderstorms. The largest of these arroyos are the so-called Rio Paguate and Arroyo Concho, which drain the area north of the Rio San Jose, and the Arroyo Colorado, which drains a broad valley to the south. The Arroyo Salado drains the northeast corner of the area and joins the Rio Puerco to the east.

FIELDWORK

The discovery of the Jackpile and other large uranium deposits on the south margin of the San Juan Basin stimulated scientific as well as economic interest in the region. To determine the relations between the uranium deposits and the regional geology, the U.S. Geological Survey, on behalf of the Raw Materials Division of the Atomic Energy Commission, studied the uranium deposits and mapped a large area surrounding them.

Robert H. Moench and Willard P. Puffett spent 3 months in the summer of 1955 mapping the Mesa Gigante area and studying the Sandy mine area. In 1956, John S. Schlee and Moench, assisted by Wilfred B. Bryan and Frank S. Hensley, spent 6 months mapping and studying the Jackpile and other mines. Moench and Schlee returned to the area on several occasions in 1957 and 1960.

Because topographic maps were not available, mapping was done on U.S. Geological Survey and U.S. Forest Service aerial photographs, at scales of 1:20,000 to 1:28,000. Six quadrangle maps (Moench, 1963b, c; Moench and Puffett, 1963a, b; Schlee and Moench, 1963a, b; see fig. 1, this report) were then compiled by means of a Kelsh plotter on U.S. Geological Survey topographic base maps at a scale of 1:24,000 when these maps became available in 1957. Three other quadrangle maps (fig. 1, GQ–354, 355, 371) were compiled by the same method on planimetric maps at a scale of 1:12,000 and were recompiled at 1:24,000 when U.S. Geological Survey topographic maps became available in 1962. Detailed mine mapping was done by tape and compass and planetable methods.

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PREVIOUS WORK

The first comprehensive geologic study of the region was by Hunt (1936; 1938) who was primarily concerned with the coal deposits and stratigraphy of the Cretaceous rocks, the major structural features of the region, and the igneous rocks of the Mount Taylor volcanic field. Earlier literature concerning various aspects of the geology of the region is voluminous and dates back as far as 1850. (See Hunt, 1936, p. 33–35; 1938, p. 53.) Hunt's work was part of a larger study of the coal deposits and stratigraphy of Cretaceous rocks in northwestern New Mexico (Sears and others, 1941). About concurrently with Hunt's work, Bryan and McCann (1936, 1937, 1938) studied structural and geomorphic aspects of the Rio Puerco and Rio Grande regions to the northeast and east, and the results of their studies bear strongly on our study of the Laguna district. More recent publications dealing with many facets of the geology of the Laguna and nearby areas are numerous and are cited throughout the text.

STRATIGRAPHY

Exposed sedimentary strata in the Laguna district range in age from Triassic to Late Cretaceous. This sedimentary column totals about 3,800 feet in thickness and is underlain by about 4,500 feet of concealed Triassic, Permian, and Pennsylvanian sedimentary rocks; the Pennsylvanian rocks rest on Precambrian gneissic rocks. The total original thickness of Cretaceous sediments in the Laguna district is not known, but about 5,000 feet of

Cretaceous strata has been recorded in areas to the north (Wood and Northrop, 1946; Dane, 1948). In the Laguna district possibly as much as 11,000 feet of Palezoic and Mesozoic strata lay above the Precambrian basement in latest Cretaceous time. An unknown thickness of early Tertiary sediments and at least half the original thickness of the Cretaceous strata have been completely removed by erosion.

Marine conditions generally prevailed in the region during Pennsylvanian time, when the thick deposits of the Magdalena Group accumulated on Precambrian rocks. After a brief interval of continental sedimentation (Permian Abo Formation), restricted marine deposition occurred in Permian time, and the Yeso and San Andres Formations were laid down (Kelley and Wood, 1946). Continental conditions prevailed during Triassic time, when the Chinle Formation accumulated. In Jurassic and possibly Early Cretaceous time, continental and subordinate shallow marine (possibly lacustrine in part) sedimentary strata accumulated to a thickness that may have exceeded 1,300 feet, forming successively the Entrada, Todilto, Summerville, Bluff, and Morrison Formations. Extensive tilting and erosional truncation followed. In Late Cretaceous time the region was invaded by the Mancos Sea. During transgression of this sea, fluvial and near-shore deposits of the Dakota Sandstone were laid down and then buried by the thick Mancos Shale and, later, by the intertonguing regressive and transgressive strata of the Mesaverde Group and Mancos Shale. After an additional unknown thickness of marine and continental sediments had accumulated in Late Cretaceous and Early Tertiary time, alternating uplift and erosion began. Also during the late Tertiary and Quaternary, igneous sills and dikes were emplaced, the Mount Taylor volcano formed, and numerous basaltic flows were extruded from pipes and fissure vents.

In the following descriptions the rock colors are based on the "Rock-Color Chart" of the National Research Council (Goddard and others, 1948), stratification and cross-stratification terminology is that of McKee and Weir (1953), grain-size designations are those of Wentworth (1922), and compositional terms are those of Pettijohn (1957). The term "sedimentation unit" is used in the sense proposed by Otto (1938, p. 575) who stated: "The sedimentation unit at any sampling point is that thickness of sediment which was deposited under essentially constant physical conditions." In this report a "stratigraphic unit" is a single body of sedimentary rock that is shown on the quadrangle maps, and it includes formations, members, and informal map units; "stratigraphic zone" is one or more sedimentation unit that is not shown on the quadrangle maps.

SEDIMENTARY ROCKS

CHINLE FORMATION

The Chinle Formation, of Late Triassic age, is exposed in a broad belt along the south side of the Laguna district in the South Butte, Dough Mountain, and Mesa Gigante quadrangles (fig. 1). Here it is divided into the Petrified Forest Member, which is a thick and widespread mudstone unit, and the overlying Correo Sandstone Member, which is a relatively thin sandstone and conglomerate unit that is restricted to the south side of Mesa Gigante and to sparse outcrops south of Mesita. The base of the formation is not exposed, but Kelley and Wood (1946) suspected that the Chinle is more than 1,000 feet thick in the Mesa Lucero area, a short distance southeast of the Laguna district. The Entrada Sandstone, of Late Jurassic age, unconformably overlies the Chinle Formation; the contact is sharp and irregular. Coarse sandstone and basal quartz pebble conglomerate of the Entrada locally fill channels cut several feet into Chinle strata.

PETRIFIED FOREST MEMBER

The Petrified Forest Member is exposed at the margins of the broad valley of Arroyo Colorado, but within the valley it is largely covered by a thin veneer of Recent alluvial and eolian deposits. Because the depth of erosion into this member is generally less than 200 feet, the member cannot be described completely.

The Petrified Forest Member is composed of grayish-red slightly calcareous siltstone and mudstone showing some light-greenish-gray mottling; stratification is inconspicuous. Evidently much of the clay is bentonitic, for the unit weathers to form a frothy-surfaced slope.

This unit is the same as the red-shale member of the Chinle Formation described by Kelley and Wood (1946) and Silver (1948, p. 73). John H. Stewart and Richard F. Wilson (written commun. 1956), from their regional study of the Triassic System, correlated this unit with the Petrified Forest Member of Arizona.

CORREO SANDSTONE MEMBER

The Correo Sandstone Member is best exposed in a prominent bench just south of Mesa Gigante quadrangle (fig. 1), and parts of this outcrop extend northward into the mapped area. The unit also caps several low hills between this exposure and Dough Mountain, in the Dough Mountain quadrangle to the southwest.

The member, which is as much as 100 feet thick, is composed mostly of sandstone but contains abundant lenses of conglomerate at and near the bottom and beds of siltstone near the top. The sandstone is subarkosic to arkosic, fine to coarse grained, poorly to well sorted, and firmly cemented. The detrital constituents average 45 percent quartz, 5–6 percent feldspar, 3 percent chert, and 3 percent rock fragments; trace amounts of mica, tourmaline, zircon, and magnetite(?) are also present. Biotite and muscovite are conspicuous in hand specimens. Quartz grains are angular to rounded and exhibit secondary overgrowths. Feldspar grains, of both plagioclase and microcline, are subequant and angular and are partly altered to clay along cleavage traces. Rock fragments consist of angular siltstone, metaquartzite, limestone, and rounded clay galls. Calcite, which commonly embays detrital grains, and quartz are the main cementing agents; detrital clay and fine-grained quartz are local cementing agents.

The conglomerate contains fragments of sandstone, siltstone, light-greenish-gray to nearly white limestone, coarse-grained quartz, and pegmatitic feldspar set in a matrix of poorly sorted calcite-cemented sandstone. The largest fragments in most conglomerate strata are large well-rounded pebbles; disk-shaped cobbles as much as 7½ inches in diameter have been found. Some limestone pebbles are composed of coarse calcite, others, of fine-grained calcite with scattered angular grains of quartz.

Small to medium-scale trough cross-stratification is common throughout the unit. Twenty-five cross-stratification planes had an average strike and dip of N. 67° E., 19° NW. These limited data suggest a northwest direction of sediment transport.

ORIGIN

The Chinle Formation is of terrestrial origin. The Petrified Forest Member may represent a thick flood-plain deposit (Kelly and Wood, 1946), but the presence of swelling bentonitic clay suggests that the unit also contains abundant altered volcanic material. The Correo Sandstone Member has the characteristics of a fluvial channel deposit. The inferred northwesterly sediment-transport direction indicates a source area to the southeast. Because limestone is known to be unstable in transport (Plumley, 1948), the presence of limestone pebbles and cobbles indicates that the source was nearby. This source area was partly underlain by sedimentary rocks (as indicated by limestone, sandstone, and siltstone rock fragments and by rounded quartz grains with worn overgrowths) and possibly partly by igneous and metamorphic rocks (suggested by mica, tourmaline, angular quartz and feldspar grains, and by metaquartzite rock fragments).

ENTRADA SANDSTONE

The Entrada Sandstone, of Late Jurassic age, forms benches and a high vertical cliff that extend west to southwest through the South Butte, Dough Mountain, and Mesa Gigante quadrangles (fig. 1). In the Laguna district it comprises three distinct units: a discontinuous basal sandstone unit, a medial interbedded mudstone, siltstone and sandstone unit, and an upper sandstone unit. The upper unit is thickest, ranging from 80 to nearly 200 feet in thickness, and forms an extensive sheet over much of the Colorado Plateau, extending westward a short distance into Arizona, and northward into Colorado and Utah (Harshbarger and others, 1957, fig. 25).

Assignment of the upper unit to the Entrada Sandstone is now generally accepted, but assignments of the underlying units are controversial (table 1). On the basis of Dutton's (1885, p. 137) type section near Fort Wingate, N. Mex., Silver (1948) referred all the beds of the Entrada Sandstone of the present report to the Wingate Sandstone, but he noted (Silver, 1948, p. 74) that his units are equivalent to those in the revised nomenclature of Baker and others (1947, p. 1666).

TABLE 1.—Stratigraphic assignments of the Entrada Sandstone

Silver (1948)		Baker, Dane, and Reeside (1947) Rapaport, Hadfield, and Olson (1952)	This report	
Wingate sandstone	Upper cliff-forming member	Entrada sandstone	Entrada Sandstone	Upper sandstone unit
	Middle slope-forming member	Carmel formation		Middle siltstone unit
	Lower cliff-forming member	Wingate sandstone		Lower sandstone unit

Baker, Dane, and Reeside (1947, p. 1666) and Rapaport, Hadfield, and Olson (1952, p. 20) assigned the medial siltstone and lower sandstone units to the Carmel Formation and Wingate Sandstone, respectively, on the basis of similarities between the stratigraphic sections south of Laguna and in western New Mexico and eastern Arizona. Harshbarger, Repenning, and Irwin (1957) recognized a medial silty facies of the Entrada Sandstone that is very similar to the Carmel Formation and extends well into New Mexico, but they doubted that the Carmel Formation extends very far eastward from Arizona into New Mexico. In the Laguna district the medial siltstone and the upper sandstone intertongue and one unit thickens largely at the expense of the other. For these reasons, we consider both to be facies of the Entrada Sandstone.

We assign the lower sandstone unit to the Entrada Sandstone because the lower and upper sandstone units are lithologically and mineralogically similar and because we found no evidence of a hiatus at the top of the lower unit. If Silver's correlation of the lower sandstone unit with the Wingate is correct, evidence of a hiatus would be expectable because the Wingate and Entrada are, respectively, of Triassic and Late Jurassic age (Harshbarger and others, 1957, p. 25). Instead of expectable scours, or a veneer of gravel, the contact between the lower sandstone and the siltstone units is sharp and even. No evidence of angularity between the lower and middle units was found.

Mineralogic similarity between the lower and upper sandstone units strengthens the assignment of the lower sandstone unit to the Entrada. Six specimens of sandstone (two each from the lower, middle, and upper units) were collected at Petoch Butte in the South Butte quadrangle (fig. 1) and studied in thin section. Modal analyses of each thin section were made by the point-count method (200 points each), and the resulting data were combined for each of the three units. The two samples of the lower sandstone unit contain an average of 54 percent quartz, 6 percent total feldspar, 2 percent chert, and 8 percent rock fragments. Samples of the upper sandstone unit contain 52 percent quartz, 6 percent total feldspar, 2 percent chert, and 12 percent rock fragments. The samples of sandstone from the middle unit are more quartzose and contain an average of 61 percent quartz, 5 percent total feldspar, and 6 percent rock fragments; one specimen contains less than 1 percent chert, the other, 10 percent chert. Small amounts of colorless rounded zircon, rounded yellow-green or green tourmaline, and subangular to subrounded garnet are present in all thin sections, and rounded apatite and rutile are present in most. The proportion of fine detritus, calcite, and voids in the matrix is extremely variable within each of the three units.

LOWER SANDSTONE UNIT

The lower sandstone unit unconformably overlies the Chinle Formation on Petoch Butte, in the extreme southwest corner of the mapped area, where it is part of an outcrop belt that extends eastward for about 4 miles from the west margin of the area (fig. 1, GQ–355). To the east the middle silty unit rests directly on Chinle strata at most places; small discontinuous lenses of the lower sandstone unit are exposed locally. Where well exposed, the lower sandstone unit forms a prominent bench or vertical cliff.

The lower sandstone unit thins from slightly more than 30 feet thick at Petoch Butte to a knife edge about 6 miles to the northeast, and it varies greatly in thickness locally. Deep scours at the base of the unit contain coarse sandstone and, locally, quartz pebble conglomerate, particularly at Petoch Butte.

The unit is light brown (5*YR* 6/4) and is composed mainly of fine- to coarse-grained sandstone firmly cemented by calcite and subordinate quartz overgrowths. The unit tends to coarsen southward and downward. At its north edge it is composed of fine-grained sandstone, whereas at Petoch Butte, to the south, it contains much coarse-grained sand and, in the basal scours, some quartz pebble conglomerate. The rock is generally fairly well sorted; most coarse grains are concentrated in thin laminae. Medium-scale festoon cross-stratification is conspicuous.

MIDDLE SILTSTONE UNIT

The middle siltstone unit is 35–40 feet thick at Petoch Butte and on the south side of Mesa Gigante and 75–85 feet thick near and west of the Crackpot mine (fig. 1, GQ–355). The bulk of the siltstone unit is soft and forms a steep slope between the two bench-forming sandstone units.

The middle unit is composed mainly of siltstone but includes some sandstone. The siltstone is light brown (5*YR* 6/4) to pale reddish brown (10*R* 5/4) and locally mottled light greenish gray (5*GY* 8/1). It is slightly calcareous, friable to firmly cemented, and laminated to thinly bedded; in places it is thinly cross-laminated. The sandstone is thin to very thin bedded, light brown (5*YR* 6/4) to grayish orange pink (5*YR* 7/2), fine to very fine grained, well sorted, well cemented with calcite, and structureless to faintly laminated. The strata generally form small benches on the sloping surface. Near the base of the unit, sandstone beds are sparse and very thin; near the top they are relatively thick and are separated by thin siltstone beds. The upper contact is chosen as the top of the uppermost siltstone stratum. At Petoch Butte the uppermost sandstone strata below the contact are fine grained, but they coarsen northward along the outcrop and merge with the upper sandstone unit of the Entrada Sandstone.

UPPER SANDSTONE UNIT

The upper sandstone unit, the main part of the Entrada Sandstone in the area, extends as a great sheet throughout much of the Colorado Plateau and some adjoining areas. The thickness of the upper unit in the Laguna area ranges from about 80 to nearly 200 feet; at Petoch Butte it is about 195 feet; on the south side of Mesa Gigante, about 137 feet; and near the Sandy and Crackpot mines and farther west, 80–95 feet. The upper sandstone unit apparently thickens southeastward, and the middle siltstone unit apparently thickens northwestward; the two units intertongue, indicating that they are, in part, time equivalents.

The upper contact of the upper unit generally is sharp and well defined. Locally, however, the overlying Todilto limestone and the upper sandstone bed intertongue within an interval of 5 feet or less.

The upper sandstone unit is planar and trough cross-stratified. Individual sets are as much as 10 feet thick, and cosets (containing several sets of cross-strata) are horizontally truncated at wide intervals by thin even-bedded cosets. Typically the upper 5–10 feet of the unit is thinly even bedded to laminated. In places, however, cross-stratified sets are directly overlain by limestone of the Todilto Formation; such sets look like buried sand dunes.

Cross-strata dip most commonly and most steeply southward. Figure 2 shows the direction and amount of dip of cross-strata plotted on the lower hemisphere of a Schmidt equal-area projection. One diagram represents readings from the area of the Sandy mine (less than 1 sq mi); the other represents readings from widely scattered localities along the entire belt of Entrada outcrop.

Grain size increases downward and southward in the unit. In exposures between the Sandy and Crackpot mines and farther west, the upper sandstone unit is fine to very fine grained near its base and mostly very fine grained near its top. On the south side of Mesa Gigante the grain size ranges from very fine to medium, but here the coarsest material is mostly near the middle of the unit. At Petoch Butte, in the southwest corner of the mapped area, the unit is coarse grained near its base and very fine grained near its top.

The upper sandstone unit is fairly well sorted throughout the area. Though single specimens may contain both fine and coarse material, the coarse grains are generally distributed in thin laminae in otherwise fine-grained rock.

The detritus of the sandstone consists of 70 to more than 80 percent quartz, 8–10 percent feldspar (mostly fresh microcline and lesser amounts of strongly altered plagioclase), small amounts of chert, and, locally, abundant rock fragments (quartzite and quartzose schist). The larger grains are well rounded, but roundness decreases with decreasing grain size. Rounded quartz overgrowths are recognized in most thin sections. Accessory minerals include magnetite, ilmenite(?), garnet, zircon, epidote, tourmaline, hornblende, muscovite, biotite, apatite, rutile(?), and hypersthene.

Calcite, the principal cement, is mostly fine grained and firmly binds most of the sandstone. Most sand grains are also coated with a thin film of moderately to strongly birefringent, probably illitic clay.

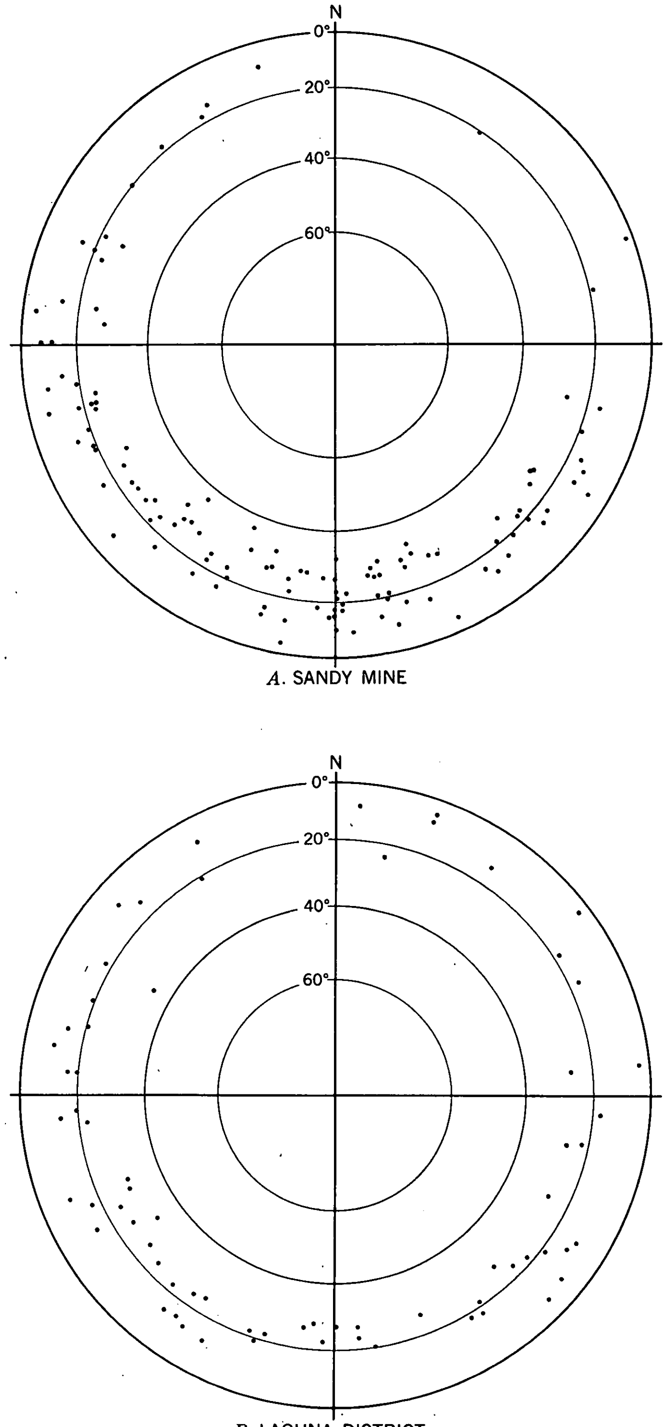

FIGURE 2.—Orientation of crossbedding in upper sandstone unit, Entrada Sandstone. Amount and direction of dip plotted on lower hemisphere of Schmidt equal-area projection.

ALTERATION

The lower part of the upper sandstone unit is pale red to light brown and moderate orange pink; the upper part has been altered to hues of very light gray, very pale orange, or light yellow. For convenience the two are called the red and white parts. The thickness of the white part averages about 30 feet but ranges from about 8 feet in places on the south end of Mesa Gigante to more than 70 feet on Petoch Butte (fig. 1, GQ–355). According to Silver (1948, p. 76), the white part thickens southward. In most exposures the boundary between the red and white parts is sharp; but as it locally cuts sharply across bedding (fig. 3), it has no stratigraphic significance. Where the white part thickens in the southern part of the mapped area, its lower boundary is gradational. A thin mottled grayish-red zone, which similarly cuts across sedimentary features, is commonly present near the base of the white part. Though the boundary between the red and white sandstones locally crosscuts the strata, within small areas it is roughly parallel to the top of the Entrada; where the Entrada was deformed by Jurassic folding, the alteration boundary also appears to have been folded.

Petrographic studies indicate that the white part formed at the expense of the red, and they suggest that the grayish-red part represents an intermediate stage of alteration. The red part is colored by finely disseminated hematite dust on sand grains and in partly argillized feldspars, but it also contains detrital magnetite and ilmenite(?), partly altered to leucoxene and hematite. The red sandstone is very porous and is partly cemented with fine-grained calcite. The white sandstone does not contain any hematite or magnetite, and the ilmenite(?) is completely altered, mainly to leucoxene. The white sandstone is cemented with calcite, mostly in large optically continuous poikilitic crystals. The local yellow hue on outcrops is imparted by hydrous iron oxides which formed by recent weathering of pyrite. In the grayish-red part, hematite is present, black opaque minerals are more altered than in the red zone, and two generations of calcite can be recognized: (1) fine-grained calcite in irregular rounded masses between detrital quartz and feldspar and outlined by dusty hematite, and (2) coarse poikilitic calcite, which surrounds the first generation. Microscopic examination suggests that the abundance of quartz overgrowths and the types of clay do not change from one color zone to another.

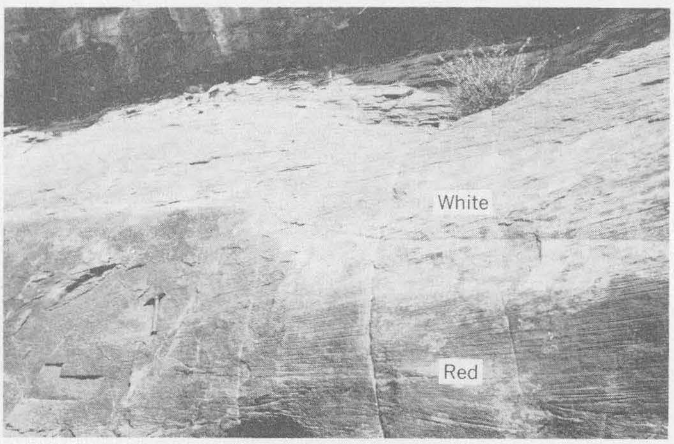

FIGURE 3.—Boundary between red and white parts of Entrada Sandstone, Sandy mine. Note that color boundary is irregular and oblique to bedding.

Several minor elements change in abundance from unaltered to altered sandstone (table 2). Iron shows an obvious decrease from unaltered to altered rock, and both specimens of grayish red sandstone show intermediate amounts. The red and grayish-red colorations may reflect differences in crystalline form and distribution of hematite, rather than amount. Vanadium also shows a marked decrease in abundance from unaltered to altered sandstone. Titanium, silver, copper, lead, zinc, and zirconium show corresponding decreases, but possibly only copper and lead decrease significantly. Zirconium no doubt reflects the distribution of zircon, which is not noticeably altered. Magnesium, manganese, boron, barium, and chromium show no consistent change. Strontium and sodium (not listed in table 2) increase slightly in the altered sandstone, but probably not significantly. The data on uranium are inconclusive but suggest a decrease from unaltered to altered rocks.

Because the altered zone boundary appears to predate the Jurassic folding, alteration probably took place shortly after Jurassic sedimentation. Alteration might be related to Todilto deposition, but the nature of the process is unknown.

TABLE 2.—*Minor-element distribution in red, grayish-red, and white Entrada Sandstone, Sandy mine*

[Analyst, method, and units: Fe_2O_3, Dwight L. Skinner, volumetric, percent; V_2O_5, Wayne Mountjoy, colorimetric, percent; U, Edward J. Fennelly, fluorometric, percent; all others, John C. Hamilton, semiquantitative spectrographic]

Sample No. and type	Outcrop color	Fe_2O_3	V_2O_5	U	Ti	Ag	Cu	Pb	Zn	Zr	Mg	Mn	B	Ba	Cr	Sr
PWR-5a; channel; 25-ft thickness.	Red	1.58	0.004	0.0002	0.15	0.00015	0.003	0.015	0.03	0.015	0.3	0.15	0.003	0.03	0.0003	0.0015
SMP-10; chips; 2-ft intervals, 20-ft thickness.	Grayish-red.	1.37	.002	.0003	------	------	------	------	------	------	------	------	------	------	------	------
PWR-5b; selected specimen	Grayish-red.	.82	.001	.0002	.15	0	.0015	0	0	.007	.15	.15	.003	.03	.0003	.0015
PWR-5c; selected specimen	White	.54	.001	.0001	.07	0	.0007	0	0	.007	.3	.15	.003	.03	.0003	.003
Spectrographic sensitivity (approx.)					.0002	.0001	.0001	.001	.02	.001	.0005	.0002	.002	.0002	.0001	.0002

ORIGIN

Throughout Late Jurassic time a highland extended east-west through parts of Arizona and New Mexico (McKee and others, 1956), supplying sediments northward to a broad basin of sedimentation. Harshbarger, Repenning, and Irwin (1957, p. 44) called this same area the Mogollon Highland. The southward coarsening of both sandstone units of the Entrada Sandstone, combined with the thickening of the upper sandstone unit, and corresponding thinning of the middle siltstone unit, indicate that the Mogollon Highland was the source of the Entrada sediments. Cross-stratification data, however, do not support this conclusion and suggest, probably erroneously, that the sediments were transported from north to south. This apparent inconsistency can be reconciled by postulating that the sands were transported by streams northward from the Mogollon Highland and were reworked by prevailing northerly winds.

The lower sandstone unit locally channels deeply into the Chinle Formation and in these scours contains much gravel; a fluvial origin in part is thus indicated.

As the middle silstone unit is thinly even bedded, it was probably deposited in shallow water or on a tidal flat. During the later stages of deposition, the shoreline moved generally northward but probably fluctuated, so that the upper sandstone unit and the silstone unit intertongue. If this origin is correct, streams from the Mogollon Highland may have transported Entrada sands northward and deposited them on a broad alluvial plain, and the fluvial character of these sands perhaps was destroyed by strong onshore winds. Climate of the time was probably arid, and conditions may have been ideal for strong onshore northerly winds.

TODILTO FORMATION

The Todilto Formation of Late Jurassic age is composed of a thin but extensive unit of limestone and an overlying, considerably thicker but less widespread unit of gypsum-anhydrite. The limestone caps a low bench on the south end of Mesa Gigante (fig. 1, GQ–210, 212) and the high south-facing cliff between the Sandy and Crackpot mines and farther west (fig. 1, GQ–355, 354). A thin limestone unit is also exposed on Petoch Butte, in the southwest corner of the South Butte quadrangle. These exposures are near the south margin of a broad basin of Todilto deposition that covered most of northwestern New Mexico and extended well into Colorado (James C. Wright, written commun., 1959). The gypsum-anhydrite unit may be largely anhydrite in the subsurface, as indicated by Anaconda's diamond-drill hole 111 at the Jackpile mine (hereafter referred to as DDH–111). In weathered outcrops the unit is chiefly gypsum. A breccia unit, which is commonly exposed near the margins of the gypsum, probably formed recently; but it is described here as a third unit of the Todilto because of the association. The stratigraphic relations of all of these units are shown in figure 4.

Gregory (1917, p. 55) defined the Todilto from its exposures in Todilto Park, N. Mex., near the Arizona border. Northrop (1950, p. 36) and Rapaport, Hadfield, and Olson (1952, p. 23) extended use of the name to exposures in northwestern New Mexico, including the Laguna district.

LIMESTONE UNIT

The limestone unit of the Todilto is divisible into a stratified zone and an overlying massive, or structureless, zone. Together the zones range in thickness from about 2 feet at Petoch Butte, in the southwest corner of the mapped area, to as much as 36 feet near the Crackpot mine (fig. 4). Where overlain by the main, gypsum unit, as north of U.S. Highway 66, the limestone is generally less than 10 feet thick.

The stratified zone of the Todilto limestone unit is thin but continuous (fig. 4). It is laminated to thinly laminated. The lower contact is generally sharp, but at places limestone and Entrada Sandstone are thinly interbedded and interlaminated in a zone about 5 feet thick. The contact between the stratified and massive zones is indefinite in most exposures. At places the uppermost foot or two of the stratified zone is sugary or granular in texture and grades upward into massive limestone. Elsewhere, uppermost laminated limestone grades laterally into massive limestone. Where gypsum overlies stratified limestone, the contact is sharp; and where leached breccia overlies stratified limestone, the upper foot or two of stratified limestone appears to have been sheared off. Laminated limestone may grade upward to chip breccia, which in turn may grade upward to leached breccia.

The stratified limestone is typically light to medium gray, with a bluish hue, and contains a few thin lenses of white gypsiferous sandstone (fig. 4). Most specimens give off a distinct fetid odor when broken. The limestone cleaves along thin siltstone laminae, which, where closely spaced (less than 0.1 in. apart), give the rock a papery fissility; where the siltstone laminations are about a foot apart, the rock splits into slabs. All variations of laminae spacing are generally present and show no consistent stratigraphic position.

Most of the rock in the stratified zone is very fine grained, but at places the limestone near the top of the zone has a coarse sugary texture, with crystals averaging 1 millimeter across. Thin sections of stratified limestone show thin laminae composed of fine-grained calcite separated by thinner layers of clastic silt and clay-sized silicates. In some specimens, silt-sized quartz and

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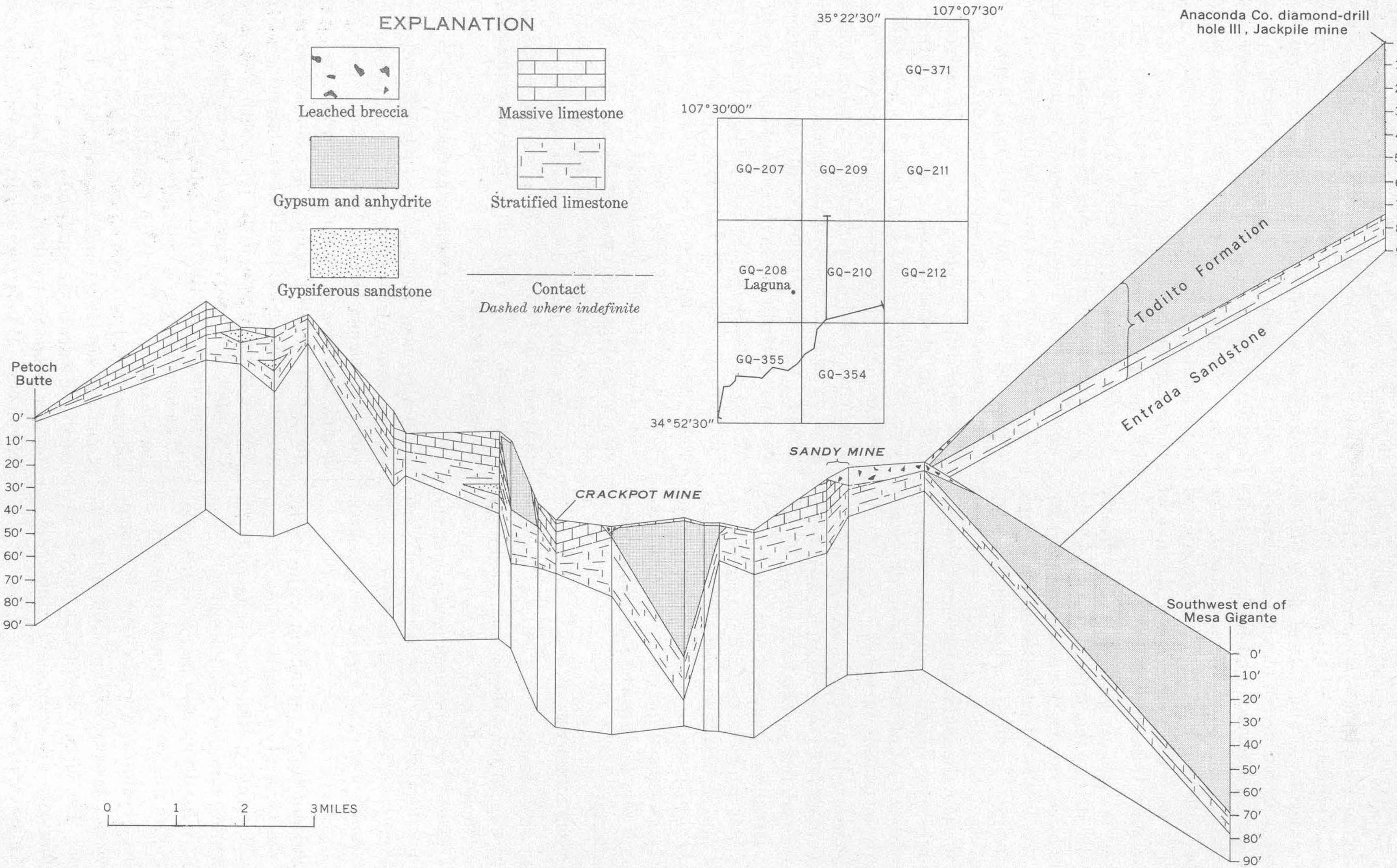


FIGURE 4.—Diagram of Todilto Formation.

microcline grains are sparsely distributed along a single surface. In others, very fine grained calcite-cemented sandstone and siltstone form thin laminae. In addition to quartz and smaller quantities of microcline, the detrital fraction includes trace amounts of alter plagioclase, chert, zircon, tourmaline, muscovite, and leucoxene. Organic laminae (Anderson and Kirkland, 1960, p. 39) have not been positively identified, but a few opaque wavy paper-thin laminae, possibly of carbonized organic material, have been seen between laminae of other materials in some thin sections.

The massive zone is discontinuous and varies greatly in thickness; locally it is as much as 15 feet thick (fig. 4). Typically its upper surface is extremely irregular, so that it forms closely spaced knolls several feet high on topographic benches. Because the massive limestone is much more resistant to erosion than the overlying Summerville Formation, the surface of the knolls represents approximately the original contact. Massive limestone and the basal part of the Summerville Sandstone are commonly intimately mixed.

The massive limestone is various shades of gray to grayish blue and emits a fetid odor when broken. It is mostly very fine grained, but coarser calcit is commonly distributed along irregular fractures and locally fills vugs. Folded laminae can be recognized in many specimens. Viewed in thin section the limestone is a mosaic of calcite, with sparsely disseminated grains of very fine sand to silt-sized fragments of quartz and some microcline. Local wisps of very fine grained limestone appear to be deformed laminae.

GYPSUM-ANHYDRITE UNIT

The gypsum-anhydrite unit of the Todilto is exposed north of U.S. Highway 66 near Mesita and around the south end of Mesa Gigante. It is 74 feet thick in anaconda's DDH–111 at the Jackpile mine and about the same thickness at one locality on the south end of Mesa Gigante. A thick but areally restricted lens of gypsum-anhydrite is also exposed north and west of the Crackpot mine (fig. 4).

At the surface the unit forms prominent white knolls or hummocks on the typically broad benches between the underlying cliff-forming limestone beds and the overlying slope-forming Summerville Formation. The tops of the knolls are locally 20 feet or more above the base of the flat-lying Summerville Formation nearby.

The base of the gypsum-anhydrite unit is sharp, though highly irregular because of the folds in the underlying limestone. The upper contact is rarely exposed, but the hummocks are commonly capped by a 6-inch-thick bed of massive limestone.

The original character of the gypsum-anhydrite unit possibly has been obscured by a complex history of dehydration and hydration. At the surface the sulfate is entirely gypsum. In DDH–111, however, the unit is composed almost entirely of medium-gray anhydrite, with a small amount of gypsum at the top. Anhydrite crystals average about 1 mm in diameter. Stratification is obscure, but the lower 36 feet of anhydrite contains thin irregular laminae of limestone. According to Anderson and Kirkland (1960, p. 40), the cyclic lamination that characterizes the limestone can be seen in outcrops of gypsum as well. They recognized a transition zone in which laminae of gypsum are added to the limestone-carbonaceous-detrital sequence. In DDH–111 a thin zone of chip conglomerate (or breccia) is associated with gypsum at the top of the unit.

The assumption, based on data from one drill hole, that anhydrite is dominant in the subsurface is corroborated by thermodynamic data. According to MacDonald (1953, p. 894), gypsum is not stable below a certain depth that depends on the regional temperature gradient. Below a possible transition zone in which both gypsum and anhydrite appear, no gypsum will be found. Goldman (1952, p. 61) noted that gypsum is rarely reported from depths below 2,000 feet in the Gulf of Mexico coast salt domes. He suggested that in the Sulfur salt dome in Louisiana, gypsum is generally stable above a depth of about 1,183 feet and anhydrite is stable below this depth; this suggestion is in accord with the data of MacDonald (1953). Because the maximum depth of burial of the gypsum-anhydrite bed of Todilto probably exceeded 6,000 feet, any original gypsum must have dehydrated to anhydrite. As the anhydrite in DDH–111 is now at a depth of slightly more than 1,000 feet, it is probably unstable in the presence of water.

LEACHED BRECCIA

Locally, near the apparent depositional margins of the gypsum-anhydrite unit, a brown porous rock, here termed "leached breccia," is exposed. Leached breccia is most abundant near the Sandy mine area, at the south margin of the main body of gypsum-anhydrite. Small amounts are also exposed at the margins of the small lens of gypsum-anhydrite just south and west of the Crackpot mine; here the change from breccia to gypsum occurs within an interval of a few feet.

Leached breccia is typically light brown to pale yellowish brown and grayish orange, owing to finely disseminated hydrous iron oxides. It is composed of limestone and sandstone and is cemented with ferruginous calcite or calcareous sandstone and siltstone. Voids in the rock probably resulted from the leaching of gypsum fragments. Where thoroughly leached, the rock has a honeycomb appearance, with cavities separated by thin septa of ferruginous granular calcite. The cavities are lined with minute crystals of rhombohedral and scalenohedral calcite. The rock grades from vuggy fine-grained limestone chip breccia to sandstone with sparse vugs. In some places bedded limestone grades upward within a foot or two into limestone chip breccia, and thence to leached breccia with some limestone chips. The leached breccia is sandier near its top, containing much material derived from the Summerville Formation and little from the limestone unit of the Todilto.

Imlay (1957, p. 485) recognized a similar breccia unit in Idaho, Utah, and Wyoming near the margin of an extensive gypsum unit of Jurassic age. There the former presence of gypsum is suggested by a unit of brecciated limestone and red siltstone within the basal red-bed member of the Twin Creek Limestone. He stated that "the change from brecciated beds to gypsum can be observed at the outcrop in a number of places. The gypsum is represented in the subsurface by white anhydrite."

The leached breccia should not be confused with the well-cemented mixture of Todilto and Summerville formed during the period of flowage shortly after sedimentation; the leached breccia probably formed recently, as the sedimentary cover was removed by erosion. In places intraformational folds in the limestone are truncated at their tops and are overlain by several feet of leached breccia. More significantly, in one outcrop about 6,000 feet north of the Sandy mine area, leached breccia cuts a diabase sill and includes many fragments of diabase; because the diabase was emplaced in late Tertiary or possibly Quaternary time, the leached breccia can be no older.

ORIGIN

That the Todilto Formation is largely an evaporite deposit is generally agreed, but whether deposition took place in a marine embayment or in a great lake is controversial. Citing the abundance of sulfate and the absence of chloride salts, Harshbarger, Repenning, and Irwin (1957, p. 46) believed that the Todilto was deposited from abnormal marine waters in a gulf that was connected with the Summerville sea (fig. 31 in their report). However, J. C. Wright (written commun., 1959) suggested, on the basis of abundant stratigraphic evidence, that the deposit formed in a large lake fed by drainage from the southwest.

Anderson and Kirkland (1960, p. 45) observed that even if a connection existed between the basin and the open sea, there is ample evidence of abundant fluvial inflow, and that this source of water and dissolved salts was probably predominant over a marine source.

Intertonguing relations (Silver, 1948, fig. 3C) suggest that the Todilto began to form during the final stages of Entrada deposition. Possibly limestone began to form in the center of the basin and spread laterally as the lake(?) expanded. J. C. Wright (written commun., 1959) suggested that sulfates then began to form in the central part of the basin while limestone deposition persisted along the edges, because the limestone is generally much thicker around the main body of gypsum than beneath the gypsum. The limestone-gypsum relationship in the Laguna district supports Wright's interpretation.

Anderson and Kirkland (1960) showed that the lamination in the limestone and gypsum was cyclic and postulated that the laminae represent annual varves. They estimated that the limestone unit was deposited in about 14,000 years, and the gypsum unit in about 6,000 years.

Postdepositional history of the unit is complex. During and after deposition, poorly consolidated limestone was deformed by slippage on the limbs of penecontemporaneous warps. Unconsolidated lime muds at the top of the unit apparently flowed freely into shallow depressions and in places became intimately mixed with loose Summerville sediments. These events may account for most of the structural features associated with the Todilto.

The leached breccia may have formed as a result of the hydration of anhydrite in late Tertiary or early Quaternary time subsequent to the emplacement of the diabase sills and dikes. Dominance of anhydrite in the subsurface and gypsum at the surface suggests that hydration took place as overburden was removed and meteoric waters gained access to the unit. If this hydration took place under shallow cover, the volume expansion (1.6 times) may have forced the margins of the gypsum-anhydrite bodies laterally along the contact between the Todilto and Summerville Formations, forming a breccia as it moved. As this breccia became exposed to weathering, the gypsum fragments presumably were leached.

SUMMERVILLE FORMATION

The Summerville Formation, of Late Jurassic age, is exposed in a line of cliffs that extends across the southern part of Mesa Gigante and in many buttes and mesas west and south of Mesita and Laguna (fig. 1, GQ–355, 354, 210, 212). The southernmost exposure is at Petoch Butte. In most areas the Summerville has been eroded back from the more resistant Todilto, and it is capped everywhere by cliff-forming Bluff Sandstone.

The Summerville Formation, which is composed of interstratified sandy mudstone and sandstone, ranges in thickness from about 90 to about 185 feet. It conformably overlies the Todilto Formation; the mixture of limestone and sandstone along the contact suggests that there was no depositional hiatus between Todilto and Summerville sedimentation.

Gulluly and Reeside (1928, p. 80) named the Summerville Formation from exposures on Summerville Point in the San Rafael Swell, Utah. Harshbarger, Repenning, and Irwin (1957, p. 39) recognized that this unit is traceable throughout the eastern part of the Navajo Country and correlated it with the "buff shale and brown-buff sandstone members of the Morrison formation," as recognized by Kelley and Wood (1946) and Silver (1948) in the Laguna-Lucero area, New Mexico. Harshbarger, Repenning, and Irwin (1957, p. 39) noted, however, that the boundary between their upper sandy and lower silty facies of the Summerville is gradational and arbitrary. In this report our usage of the term Summerville Formation for the lower silty facies of Harshbarger, Repenning, and Irwin (1957, p. 39) and the buff shale member of Kelley and Wood (1946) and Silver (1948, p. 77) is identical with that of Rapaport, Hadfield, and Olson (1952, p. 27) and Freeman and Hilpert (1956, p. 312). The boundary between the Summerville and overlying Bluff Formation is chosen as the top of the uppermost mudstone bed.

According to Silver (1948, p. 77, fig. 1), the Summerville Formation (his buff shale member) in the Laguna district thins and coarsens southward, and about 17 miles south of Petoch Butte it wedges out against the unconformably overlying Dakota Sandstone. Within the district it is thinnest (96 ft) on the southeast corner of Mesa Gigante and thickest (182 ft) 2½ miles west of the Crackpot mine. Elsewhere, from Petoch Butte to the Jackpile mine (DDH-111), the unit is 120 to about 150 feet thick.

In most Summerville exposures, mudstone is dominant in the lower half, whereas sandstone is dominant in the upper half. Although individual sandstone and mudstone beds may be as much as about 15 feet thick, particularly near the top of the unit, the Summerville as a whole is more characteristically thin bedded. Mudstone and sandstone strata are commonly intensely contorted, particularly near the base of the unit, and the whole unit is cut by many sandstone pipes and some intraformational faults. Similar intraformational structural features are characteristic of the formation in other parts of the Colorado Plateau (Harshbarger and others, 1957, p. 41).

The sandstone is light brown (5*YR* 6/4), moderate brown (5*YR* 4/4), and very pale orange on weathered surfaces, and generally nearly white on fresh surfaces. It is fine to very fine grained, well sorted, and friable to well cemented with calcite. Most strata are structureless, but horizontal laminae and small- to medium-scale cross-laminae can be distinguished in some strata. The sandstone is orthoquartzite to subarkose; it is composed mainly of quartz but includes small amounts of feldspar and chert, fragments of siltstone and quartzite, and trace amounts of magnetite, ilmenite, staurolite, epidote, tourmaline, zircon, garnet, apatite, monazite(?), and sphene(?). Calcite is the dominant cement. Roundness values are 0.4–0.5 (Krumbein, 1941).

The sandy mudstone strata are light brown (5*YR* 6/4), dark reddish brown (10*R* 3/4), very light gray, and moderate greenish yellow (10*Y* 7/4) on both weathered and fresh surfaces. Viewed in thin section the mudstone contains abundant to sparse fine-sand-sized particles set in an iron-stained matrix of silt and clay; the matrix forms 20 percent or more of the rock. The coarsest detrital fraction and the accessory minerals are similar to those of the sandstone, but the largest fragments are slightly more angular (roundness values 0.3–0.4; Krumbein, 1941).

Origin.—Harshbarger, Repenning, and Irwin (1957, p. 48) postulated that the Summerville Formation (their lower silty facies) was deposited during the initial transgression of the Summerville sea and that the upper sandy facies (lower part of our Bluff Sandstone) was deposited during the regression of the sea. The thin-bedded character of most of the formation is consistent with deposition in a shallow body of water or on a tidal mudflat, and also with the character of the directly underlying and overlying formations. However, the absence of fossils is difficult to reconcile with this interpretation unless the water was extremely saline; if the water was extremely saline, evaporite deposits should be more abundant than they are. Finally, the lack of sorting in the finer grained material is difficult to explain by shallow marine sedimentary processes.

The close association of well-sorted orthoquartzite or subarkose strata with poorly sorted matrix-rich sandstone and sandy mudstone strata suggests that the sediments were alternately rapidly introduced and gradually reworked. The matrix-rich rocks are probably the result of turbidity flows along the bottom of a shallow body of water. Such flows could easily have been triggered by the structural warping that is known to have begun during or shortly after Todilto deposition; this warping probably also accounts for the abundant intraformational slump features in the Summerville Formation. During the intervals between turbidity flows, wave action and bottom currents could have winnowed the fines from the turbidity-flow deposits and produced well-sorted sands.

Coarsening of grain size and thinning of the Summerville Formation southward from Petoch Butte (Silver, 1948) suggest that the source of the sediments and the depositional edge of the unit was on the flank of the Mogollon Highland to the south.

BLUFF SANDSTONE

The Bluff Sandstone, of Late Jurassic age, intertongues with the underlying Summerville and with the overlying Morrison Formation and is well exposed in cliffs on the west and south sides of Mesa Gigante and in buttes west and south of Mesita and Laguna (fig. 1, GQ–355, 354, 208, 210, 212). The thickness of the Bluff Sandstone ranges from less than 200 to nearly 400 feet, but it is about 300 feet in most areas. On Petoch Butte (fig. 1, GQ–355) the Bluff is unconformably overlain by the Dakota Sandstone and is about 220 feet thick, which is unquestionably less than its original thickness.

Two stratigraphic parts that were not mapped are recognized in the Bluff Sandstone: a lower part characterized by alternating horizontal and small- to medium-scale cross-stratified cosets, and an upper part characterized by spectacular large-scale cross-stratified cosets. The boundary between these parts, near the middle of the Bluff Sandstone, is gradational. The upper part is yellowish gray (5*Y* 7/2) to grayish yellow (5*Y* 8/4) in most of the area but is grayish yellow green (5*GY* 7/2) at South Butte (fig. 1, GQ–355). The lower part on the south end of Mesa Gigante (fig. 1, GQ–212) is mostly pale reddish brown (10*R* 5/4). Here the color boundary approximately follows the contact between the two stratigraphic parts. This color change, which expresses the distribution of hematite dust in the lower part and of pyrite in the upper part, may be due to pyritization of previously red-hued sandstone and probably has no stratigraphic significance. Westward the lower part changes to very pale orange (10*YR* 8/2) and shades of yellowish gray and becomes indistinguishable, in color, from the upper part. This color change, caused by pyritization of previously red-hued sandstone, is related to diabase and has no stratigraphic significance.

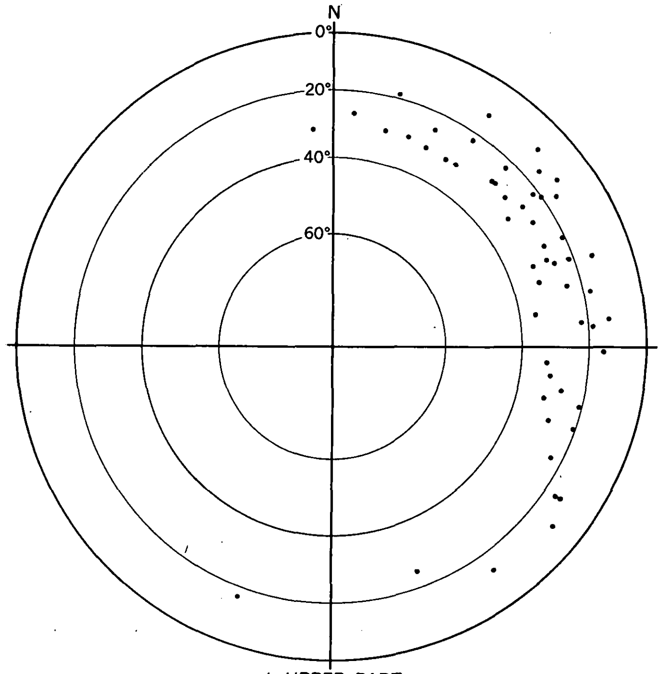
Gregory (1938, p. 58) named the Bluff Sandstone from exposures near Bluff, Utah, and assigned the unit to the basal part of the Morrison Formation. Later, Craig and others (1955, p. 134) and Harshbarger, Repenning, and Irwin (1957, p. 42) separated the Bluff Sandstone from the Morrison Formation and assigned it to the uppermost part of the San Rafael Group. Freeman and Hilpert (1956, p. 312) used this terminology and extended use of the name into the Laguna district. In the Navajo country the Bluff Sandstone was believed by Harshbarger, Repenning, and Irwin (1957, p. 42) to be a tongue of the Cow Springs Sandstone. The Cow Springs Sandstone, a thick unit of eolian sandstone west of Gallup, N. Mex., intertongues northward with the Summerville and Bluff Formations and with the Recapture Member of the Morrison Formation. As this stratigraphic sequence is exposed in the Laguna district, intertonguing relations may extend eastward from Gallup as well. If the correlation of the Bluff Sandstone in the Laguna district with the Bluff in the Navajo country is correct, the same general source area is indicated. Much of the Bluff Sandstone west of Gallup was derived from the Jurassic Mogollon Highland to the south and west (Craig and others, 1955, p. 150; Harshbarger and others, 1957, p. 43).

The Bluff Sandstone of this report is equivalent to the upper, sandy facies of the Summerville Formation of Harshbarger, Repenning, and Irwin (1957, p. 39) and to their Bluff Sandstone. It is also equivalent to the brown-buff and white sandstone members of the Morrison Formation as defined by Kelley and Wood (1946) and Silver (1948, p. 78).

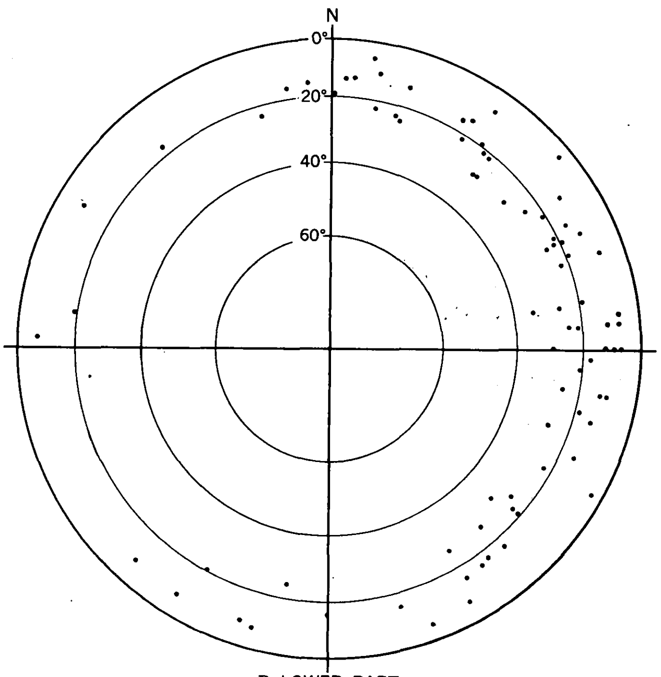
Except where the Bluff Sandstone is directly overlain by the Dakota Sandstone, marked local thickness changes apparently reflect thickening in the lower part of the unit and not relief on the upper contact of the Bluff. At one place thickening is known to be related to contemporaneous structural depression. The upper few feet of the Bluff is horizontally stratified, which indicates that the large dunes that probably characterized the terrain during most of late Bluff time were beveled and buried before the advent of Morrison sedimentation.

The lower part of the Bluff is composed of very fine to medium-grained fairly well sorted quartzose sandstone. It is well cemented with calcite and characteristically forms high vertical cliffs above the less resistant Summerville Formation. The unit is characterized by alternate thin to very thick flat-bedded and crossbedded cosets. Individual cross-strata are small to medium scale (generally less than 20 ft long) and are typically trough shaped. As shown in figure 5*B*, the dip directions of crossbedding are concentrated in the two eastern quadrants. On the basis of 81 measurements, the mean dip direction is S. 87° E., and the average inclination is 18°.

The sandstone of the lower part contains about 70 percent quartz, 1–2 percent feldspar, about 1 percent chert, and trace amounts of metaquartzite and siltstone rock fragments, magnetite(?), zircon, tourmaline, and hypersthene(?). Thin flakes of clay commonly coat sand grains. Feldspars are variably altered, and chert



A. UPPER PART



B. LOWER PART

FIGURE 5.—Orientation of crossbedding in Bluff Sandstone. Amount and direction of dip plotted on lower hemisphere of Schmidt equal-area projection.

fragments display an oolitic microcrystalline texture. Cementing material consists of calcite, quartz as oriented overgrowths on quartz grains, and small amounts of hematite. In the lower part the grains are slightly finer, less well sorted, and less well rounded than in the upper part. The hematite colors the reddish-brown sandstone and occurs as dustings on both the detrital grains and the oriented quartz overgrowths. The very pale orange or yellow sandstone contains disseminated pyrite grains and sparse to abundant concretions, which weather to limonite and hematite.

The upper part of the Bluff Sandstone is fine to medium grained and very well sorted. It is only moderatey well cemented and forms smoothly rounded exposures that slope steeply back from the top of the lower part. Sets of steeply inclined cross-strata as much as 30 feet high are not uncommon; a single stratum can be traced from the bottom to the top of such sets, and cross-stratified cosets are truncated at wide intervals by thin flat beds. The uppermost several feet of the unit is typically flat bedded. As indicated in figure 5*A*, cross-stratification dips northeastward with remarkable persistency. On the basis of 63 readings, the mean dip direction is N. 78° E., and the average inclination is 24°.

The upper part is compositionally similar to the lower part except that it contains slightly less quartz (65 percent) and slightly more feldspar (2–3 percent). Sorting is good and the grains are well rounded. The sandstone is only moderately well cemented with quartz and calcite; voids make up 15–20 percent of the rock. Quartz overgrowths are not common, and calcite tends to occur in isolated patches. Thin flakes of clay commonly coat sand grains. Pyrite is common in drill cores, and small concretions of limonite after pyrite are locally abundant.

Origin.—Harshbarger, Repenning, and Irwin (1957, p. 39, 42) suggested that the upper sandy facies of their Summerville Formation (equivalent to the lower part of the Bluff Sandstone in the Laguna district) represents nearshore regressive marine deposition. The conspicuous absence of fossils, however, does not support this interpretation. The lower part may be fluvial in part, for the cross-strata are largely trough shaped, and their average inclination (18°) is similar to that reported by Potter (1955, p. 12) for the fluvially deposited Tertiary Lafayette Formation of former usage of western Kentucky. The average eastward dip direction of the crossbedding in the lower zone of the bluff indicates that the sands were transported eastward, probably by streams originating in eastern Arizona and west-central New Mexico.

As Bluff sedimentation continued, wind activity apparently increased. The spectacular large-scale steeply inclined crossbeds of the upper part appear to characterize eolian deposits (McKee, 1953, p. 20, 22, 28, 49). The good sorting of the sand supports this interpretation. The grand scale and persistent eastward dip direction of the crossbedding suggest that large sand dunes were moved eastward by exceptionally persistent prevailing westerly winds.

MORRISON FORMATION

The Morrison Formation, of Late Jurassic age, is exposed on the sides of mesas and buttes capped by Dakota Sandstone in a belt extending northeastward across the district (fig. 1, GQ–355, 354, 208, 210, 212, 209, 211, 371). The most complete exposures are on the south end of Clay Mesa, just north of U.S. Highway 66 near Laguna, and 2½ miles north of Laguna on the road to Paguate. Here, all three members of the Morrison Formation and a thick unit of economic importance, the Jackpile sandstone, are well exposed. In ascending order the recognized members are the Recapture, the Westwater Canyon, and the Brushy Basin; the Jackpile sandstone (of local economic usage) is the uppermost unit in the Morrison Formation. The Recapture Member is composed of grayish-red and some greenish-gray mudstone, siltstone, and sandstone and a few thin layers of limestone. The Westwater Canyon Member is a widespread unit of arkosic sandstone. The Brushy Basin Member is composed largely of grayish-green mudstone containing many discontinuous sandstone layers, lithologically like the Westwater Canyon Member, and a few thin layers of limestone. The Jackpile, a locally thick unit of dominantly arkosic sandstone, is the chief ore-bearing unit of the district. The generalized stratigraphic relations of the members are shown on plate 1.

The Dakota Sandstone unconformably overlies the Morrison Formation (pl. 1). Southward from the Jackpile mine, where the Morrison is 603 feet thick, the Dakota truncates successively lower units in the Morrison; and at Petoch Butte (fig. 1, GQ–355) the Morrison Formation was completely removed by pre-Dakota erosion. Stratigraphic relations described by Schlee and Moench (1961) indicate that the Morrison thins northwestward as well. The individual members of the Morrison also appear to thin southward (pl. 1).

The Morrison Formation, which was named by Cross (1894, p. 2) from exposures near Morrison, Colo., has been recognized over much of the Rocky Mountain region. In northwestern New Mexico, Baker, Dane, and Reeside (1936) included in the Morrison all units between the Entrada and Dakota Sandstones. In more recent literature (Craig and others, 1955, p. 134; Freeman and Hilpert, 1956; Harshbarger and others, 1957) the name has been restricted to terrestrial fluvial deposits of Jurassic age that overlie beds of the San Rafael Group. All these authors recognized the three members of the Morrison Formation of this report in northwest New Mexico. Freeman and Hilpert (1956) extended use of the names Recapture, Westwater Canyon, and Brushy Basin Members to the Laguna district, and they (p. 317) informally called the light-colored sandstone unit at the top of the Morrison Formation the Jackpile sandstone bed.

Although the age of the Morrison Formation is generally accepted as Late Jurassic, Morrison sedimentation may have continued into Early Cretaceous time. The angular unconformity between the Morrison Formation and the Dakota Sandstone definitely marks a hiatus between Morrison and Dakota sedimentation, but the length of this hiatus is not known. The Jackpile sandstone is similar in character and stratigraphic position to the Burro Canyon Formation, of Early Cretaceous age, in southwestern Colorado, and the two may well be correlative. Like the Burro Canyon (Simmons, 1957, p. 2523), the Jackpile intertongues with the Brushy Basin Member of the Morrison.

RECAPTURE MEMBER

The Recapture Member is generally less than 100 feet thick in the Laguna district, and in most exposures it is less than 50 feet thick (pl. 1). In the southwestern part of the district, scours locally cut through the Recapture Member and into the Bluff Sandstone; these scours are filled with sediment of the Westwater Canyon Member.

The lower contact of the Recapture Member is generally sharp; it is marked by a downward change from the dominantly grayish red of Recapture strata to the yellowish gray and grayish yellow green of the Bluff Sandstone. Apparently the contact had little original relief. On the east side of Mesa Gigante, however, the Recapture Member and Bluff Sandstone intertongue. The contact between the Recapture and Westwater Canyon Members also is sharp. Where the Westwater Canyon Member is absent, as at the southeast corner of Mesa Gigante, the boundary between the Recapture and Brushy Basin Members is gradational.

The Recapture Member is composed of interstratified mudstone, siltstone, sandstone, and limestone. Exposed surfaces are dominantly grayish-red, but much fresh mudstone is grayish green, some of the sandstone is grayish yellow, and most of the limestone is light gray. Most of the grayish-red coloring is in the finer grained clastic rocks. Individual beds are locally as much as about 10 feet thick, but most beds are much thinner. The mudstone and siltstone are poorly sorted and contain variable amounts of fine sand grains. The sandstone is typically fine grained, clay cemented, and poorly sorted. It is composed of about 55 percent detrital quartz, abundant feldspar, and smaller amounts of chert and rock fragments. The rock fragments are altered volcanic rock, siltstone, and mudstone. Accessory minerals are tourmaline, rounded zircon, muscovite, magnetite, ilmenite, hematite, and glaucophane. Some quartz grains are bordered by worn quartz overgrowths. Feldspar grains are both altered and fresh. Clay is the major interstitial material, averaging 16 percent of the rock but locally constituting as much as 30 percent of the rock. Calcite and silica cements are locally abundant. On the east side of Mesa Gigante, discontinuous fine- to medium-grained sandstone strata contain deposits of coalified plant debris and associated small uranium deposits. Limestone beds are mostly less than 1 foot thick, but one bed more than 5 feet thick is exposed a short distance southeast of Laguna. The limestone is gray, very fine grained, and apparently structureless and unfossiliferous. Locally it is a conglomerate composed of tabular fragments of limestone and subordinate sandstone and siltstone.

WESTWATER CANYON MEMBER

The Westwater Canyon Member ranges from about 10 to 60 feet in thickness on the west side of the district and is as much as 90 feet thick at one locality on the east side of Mesa Gigante. Where thickest it is comprised of two sandstone parts separated by about 3 feet of grayish-red siltstone, green sandstone, and light-gray limestone. The unit is locally absent on the south end of Mesa Gigante. In the northeastern part of the district (pl. 1), the Westwater Canyon Member is probably exceptionally thick, though its base is not exposed. Here, the unit forms the floor of the valley of Salado Creek (fig. 1, GQ–371) and has been incised to depths of more than 100 feet. The Westwater Canyon and Recapture Members intertongue; some of the stratigraphically lowest arkosic sandstone beds in the Brushy Basin intertongue with the top of the Westwater Canyon.

At its best exposures, about 2½ miles north of Laguna and on the west side of Mesa Gigante, the Westwater Canyon Member forms a prominent bench of grayish-yellow to very pale orange well-cemented sandstone. Elsewhere it is less well cemented and forms a slope. The sandstone is poorly sorted, fine to coarse grained, and subarkosic to arkosic; pink feldspar is conspicuous in hand specimens. Pebbles of quartz and chert are locally common near the base of the unit. Quartz averages 51 percent of the rock, and fresh microcline, perthite, and variably altered plagioclase are abundant; fragments of hypabyssal igneous rocks, pegmatite, metaquartzite, limestone, and indurated siltstone are common. Fragments are both angular and rounded. Where friable, the sandstone may contain no cementing material at all; where well cemented, it contains various forms of silica or calcite cement. Silica cement is typically in the form of oriented overgrowths on detrital grains, locally as chalcedony, and rarely as bands of quartz crystals whose crystallographic axes are normal to the surfaces of the detrital grains. Small silicified logs have been found.

Small- to medium-scale trough cross-stratification is common in the Westwater Canyon Member. Cross-stratification attitudes measured at widely scattered outcrops are shown in figure 6. Although the spread in orientation is great, the dip directions are least abundant between N. 55° W. and S. 35° W., and most abundant in the opposite quadrant. This suggests that the sediments were transported in a generally easterly or northeasterly direction, which is consistent with the data for the Bluff Sandstone and Jackpile sandstone.

BRUSHY BASIN MEMBER

The Brushy Basin Member is the thickest and most widely exposed unit of the Morrison Formation. Beyond the south margin of the Jackpile sandstone the member is capped unconformably by the Dakota Sandstone (pl. 1), and its original thickness cannot be determined. Where the Jackpile sandstone crops out or is present in drill holes, the underlying Brushy Basin Member ranges from about 220 to nearly 300 feet in thickness.

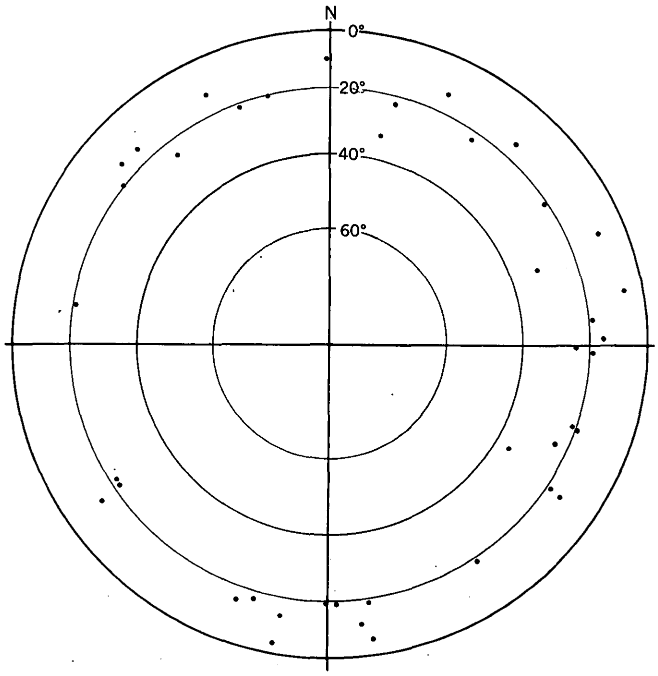


FIGURE 6.—Dip directions of crossbedding in Westwater Canyon Member. Amount and direction of dip plotted on lower hemisphere of Schmidt equal-area projection.

The Brushy Basin Member is chiefly grayish-green (5*G* 5/2) to light greenish gray (5*GY* 8/1) mudstone. Thin grayish-red (5*R* 4/2) mudstone layers occur throughout the member but are most abundant near its base. The mudstone is typically silty and sandy, but in a few places it is nearly pure clay. On fresh surfaces it shows an irregular fissility that is about parallel to stratification, but stratification is not obvious. Typically frothy weathered surfaces indicate that the rock contains abundant swelling clays. In a suite of mudstone samples from the east side of Mesa Gigante, collected and studied by W. D. Keller, montmorillonite is the dominant clay mineral. Thin-section studies show that the more firmly cemented beds of mudstone are composed of angular to rounded fine-sand- to silt-sized particles of quartz, feldspar, and rock fragments and sparse ragged plates of biotite and muscovite embedded in a dense, structureless clay matrix.

Sandstone strata lithologically similar to the Westwater Canyon Member locally make up a large part of the Brushy Basin Member. As is shown on plate 1, most of these strata are thinner and less widespread than the Westwater Canyon Member, although some are locally thick. At two localities on the south end of Mesa Gigante, 45- and 85-foot-thick deposits of coarse sandstone and granule-and-pebble conglomerate were measured. These abnormally thick deposits are localized in north-trending Jurassic synclines directly beneath the Dakota Sandstone and could be mistaken for Jackpile sandstone except that they are stratigraphically too low (about 230 ft. above the base of the Morrison). Instead, they probably correlate with a thin discontinuous unit of sandstone in the Brushy Basin on the east and west sides of Mesa Gigante.

The sandstone beds are very pale orange and form small benches on the steep slopes of Brushy Basin Member outcrops. Internal structural features are similar to those in the Westwater Canyon Member, and dip directions of cross-stratification, when plotted, show a similar broad spread, with a general trend to the east. The thick sandstone bodies on the south end of Mesa Gigante are coarser grained than most sandstone beds of the Brushy Basin, and they contain abundant lenses of pebble conglomerate. The pebbles are intergrown coarse-grained quartz and feldspar, chert, and quartzite. Sandstone from thinner strata is poorly sorted and arkosic; it contains, in addition to quartz, abundant microcline, plagioclase, and fragments of quartzite and altered hypabyssal igneous rocks. The igeneous-rock fragments contain small euhedral phenocrysts of altered feldspar embedded in a dense matrix of quartz and clay. The sandstone is cemented by Quartz and calcite. Quartz locally forms oriented overgrowths on sandstone grains or enclosing bands of crystals oriented normal to sand-grain surfaces.

Where sandstone strata of the Brushy Basin are in contact with or a short distance below the Dakota Sandstone, they commonly have a chalky-white cast, similar to that of the Jackpile sandstone. The white cast is given by kaolinite (determined by W. D. Keller), which fills pore spaces, and in places thoroughly impregnates the sandstone. The kaolinite also occurs as white clots about a quarter of an inch across, similar to those in the lower parts of the Jackpile sandstone. Where the sandstone beds diverge northward from the Dakota Sandstone, they contain less kaolinite cement, more calcite and silica cement, and more detrital feldspar and rock fragments.

Beds of dark-brown to dark-green massive strongly cemented sandstone, generally less than 5 feet thick, are sparsely distributed in most Brushy Basin exposures. This sandstone is poorly sorted and has the same detrital composition as the Westwater Canyon Member, but its cement is clay.

Thin unfossiliferous limestone strata are sparsely distributed throughout the Brushy Basin. Most beds are a foot or less thick, but one bed about 15 feet thick was found northwest of Laguna. Typically the limestone is very light gray, dense, and massive.

In the eastern and northeastern parts of the district, a stratum of red volcanic tuff less than 5 feet thick appears to be fairly continuously exposed in the Brushy Basin; it is about 100 feet above the base of the Brushy Basin Member. This stratum was not mapped, but it may prove to be a good stratigraphic marker in areas northeast of the district. In thin sections the rock appears to be made up of sharp microcrystalline relict shards solidly cemented by silica. The red color is given by finely disseminated hematite.

JACKPILE SANDSTONE OF ECONOMIC USAGE

The Jackpile sandstone is exposed directly beneath the Dakota Sandstone in a belt of outcrops that extends northeastward across the district (pl. 3). The most accessible exposures are just north of Laguna and at the Jackpile mine. Because it is the major ore-bearing unit of the Laguna district, the Jackpile sandstone was studied in greater detail than the other sedimentary rocks. The results of this study (Schlee and Moench, 1961) are summarized here.

The sandstone forms a northeast-trending belt (Potter, 1962) as much as 13 miles wide and 200 feet thick and more than 33 miles long (pl. 3). Northeastward the sandstone body broadens and divides into at least two smaller trough-shaped fingers. Because the deposit is truncated at its top by an angular unconformity, its present dimensions are smaller than its original dimensions, and it may conceivably have extended over a much wider area.

The Jackpile sandstone apparently was deposited in a broad Jurassic structural depression (Schlee and Moench, 1961, figs. 4, 11). This origin is indicated by the relations of rocks along the angular unconformity beneath the Dakota Sandstone, as seen in exposures on the southeast side of the Jackpile sandstone body, and by drill-hole information from the northwest side of the sandstone body. Further evidence is the fact that the Jackpile thickens by intertonging with the Brushy Basin Member. One tongue of the Jackpile was mapped in Oak Canyon, in the northwest corner of the Mesita quadrangle (fig. 1, GQ–210).

Local concentrations of fossil plant remains, though not abundant in the Jackpile sandstone, provide ample evidence of terrestrial origin. Silicified logs as much as 3 feet in diameter and 60 feet long are abundant in parts of the sandstone and in some places appear to have formed log jams. Their branches are gone, which suggests that the logs were transported and rolled for some distance from their place of origin. A small concentration of coalified plant debris was found in a collapse feature in the Jackpile mine, and a large bone fragment, probably from a dinosaur, was found in the Woodrow collapse feature.

Both at the surface and in the subsurface, the upper part of the Jackpile has a pervasive chalky-white cast, which reflects its kaolinite content. The lower part of the unit is yellowish gray to very pale orange. The sandstone throughout is generally fine to medium grained, poorly sorted to moderately well sorted, and friable. It is composed of detrital quartz and minor amounts of feldspar, clay galls, chert, and igneous rock fragments, and is cemented by various amounts and mixtures of clay, silica, and calcite. The unit is composed of interstratified lenticular strata that may be several feet thick. The sandstone strata may be massive or may exhibit cosets of medium-scale trough cross-lamination as much as 4 feet thick. A few discontinuous strata of greenish-gray bentonitic mudstone occur in most exposures.

Although we were unable to detect a systematic lateral or longitudinal distribution of modal or maximum grain size in the sandstone body, a vertical grain-size change is noticeable. In most places the unit is coarser grained near its base, but it has small amounts of coarse material throughout. The largest fragments found in most exposures are in the 2- to 4-mm size range (granules), but coarse pebbles (32–64 mm) occur locally, particularly at the base of the unit.

The composition of the Jackpile sandstone changes upward. Many samples from the lower part are arkose or subarkose, and many from the upper part are subarkose and orthoquartzite (Pettijohn, 1957, p. 291). Subangular to subrounded quartz grains commonly make up 80–95 percent of the detrital fraction, and angular feldspar fragments (dominantly microcline with subordinate plagioclase and perthite) make up 1–19 percent (average 5 percent) of the detrital fraction. In thin sections, grains display all degrees of alteration; some are so badly altered that only the relict outline of the grain remains, whereas others in the same thin section may be completely unaltered. Some feldspar is extensively embayed or almost entirely replaced by calcite. Other rock fragments are volcanic debris, polycrystalline quartz, chert, and mudstone. Inasmuch as most of the volcanic rock has been altered, its abundance may have been underestimated. A few greatly altered grains show relict texture of feldspar laths set in a cryptocrystalline groundmass. The dominant heavy minerals are zircon and tourmaline; less abundant are leucoxene, magnetite rutile, garnet, and sillimanite.

Near its base the Jackpile sandstone is dominantly calcite cemented; upward it becomes increasingly clay cemented. In typical thick exposures, calcite sand crystals are prevalent near the base of the unit, but these, as well as finer grained calcite, decrease in abundance upward as small clots of white clay increase in abundance; near the top of the unit the clay may thoroughly cement the sandstone. Complete mechanical analyses and X-ray analyses of clay were made on six samples from the Jackpile mine (John C. Hathaway, analyst). Kaolinite was found to be much more abundant than mixed-layered mica-montmorillonite in the clay fractions of four samples of fine- to medium-grained sandstone rich in white clay. Two samples of finer grained rocks with little visible white clay contained dominant mixed-layered mica-montmorillonite and subordinate kaolinite. Hand-picked white clay gave a good kaolinite X-ray powder pattern (determined by Moench). Sand grains throughout the unit have quartz overgrowths, commonly with euhedral crystal faces, and these overgrowths locally coalesce and bind several adjoining grains. The calcite appears to postdate the clay, but the age relations between the quartz and the calcite or the clay are not known.

As seen in thin sections, clay is present in many forms, from extremely fine grained indeterminate aggregates to clots that contain well-crystallized kaolinite booklets. In places clay forms aggregates that completely fill interstices, and in places it also coats sand grains as a single layer of plates oriented normal to the surface of sand grains. Elsewhere only isolated clots of clay are visible in thin section; these correspond to the specks of white clay seen in hand specimens and may represent thoroughly altered feldspar grains or volcanic debris. All these habits of clay may be observed in a single thin section.

KAOLINIZATION OF SANDSTONES

Although kaolin is most abundant in the Jackpile sandstone, it is probably also present wherever Jurassic sandstones are truncated by the angular unconformity at the base of the Dakota Sandstone. This relationship can be seen on the west side of Mesa Gigante and on the sides of buttes and mesas a short distance southwest of the district (toward Acoma Pueblo). In these areas the Jackpile sandstone and successively lower Morrison sandstones and the Bluff Sandstone are kaolin rich to depths of as much as 100 feet below the unconformity.

A regional study of the pre-Dakota hiatus by Leopold (1943) disclosed the presence of kaolin and kaolin-cemented sandstone at the top of the Morrison Formation in northeast Arizona and northwest New Mexico. Leopold postulated that the kaolin is a product of weathering under moist conditions that occurred prior to deposition of Dakota Sandstone. Our observations in the Laguna district (Schlee and Moench, 1961, p. 142) support Leopold's conclusion, although possibly the kaolinization reflects downward percolation of corrosive solutions as the overlying Dakota Sandstone was being deposited (H. C. Granger, oral commun., 1962). Decomposition of the relatively unstable constituents could result in formation of kaolinite and smaller quantities of other clay minerals, and it could also result in the observed relative enrichment of quartz and impoverishment of feldspar and rock fragments. Free silica liberated during the breakdown of feldspar and volcanic rock fragments may have contributed to silica cementation and to silicification of logs in the Jackpile sandstone (Schlee and Moench, 1961, p. 143).

ORIGIN

According to Harshbarger, Repenning, and Irwin (1957, p. 55), "the Morrison formation was deposited by a system of braided streams on a generally flat surface, overlying the deposits of the San Rafael group. The sediments are primarily fluvial, consisting of alternating flood-plain and channel deposits." Craig and others (1955, p. 150–152, 156–157) interpreted the Recapture Member, the Westwater Canyon Member, and the sandstone strata of the Brushy Basin Member to be deposits of streams that flowed east, northeast, and north from a source area south of Gallup, N. Mex. Much of the bentonitic clay in the Brushy Basin represents volcanic ash, and the thin limestone beds may represent lacustrine deposition (Craig and others, 1955, p. 157).

The eolian environment of late Bluff time was followed without a break by the fluvial and lacustrine environment of Recapture time. Although in the Navajo country to the west the Recapture is conglomeratic (Harshbarger and others, 1957, p. 52), in the Laguna district it contains only fine-grained clastics and limestone. This difference suggests that the source area was farther from the Laguna district and that streams were generally slower moving and lakes more abundant.

After a period of relatively quiet Recapture sedimentation, the source area in west-central New Mexico was rejuvenated, and a great apron of coarser sand spread over northwest New Mexico and adjacent States and formed the Westwater Canyon Member (Craig and others, 1955, p. 157). The paleocurrent data determined from cross-stratification in the Laguna district, shown in figure 6, are consistent with the hypothesis of a source area to the west or southwest. The composition of the detrital fragments indicates that older sedimentary, igneous, and metamorphic rocks were exposed in the source area (Craig and others, 1955, p. 157).

Streams from the same general source area continued to deposit similar sands during the formation of the Brushy Basin Member. Volcanic activity was undoubtedly more prevalent, however, and much volcanic ash was reworked by streams to form the thick bentonitic mudstone deposits. Some beds of the Brushy Basin Member probably accumulated from ash falls, for shard structure has been recognized. The thin limestone beds probably formed in scattered lakes on the broad alluvial plain.

The Jackpile sandstone may be a product of a second major rejuvenation of the source area south of Gallup. Aside from the fact that the sandstone has been extensively altered, its composition and internal structure are like those of the Westwater Canyon Member, and its cross-stratification indicates that the sediments were derived from the same direction. The beltlike shape of the Jackpile, branching in a downstream direction, could be interpreted as indicating a deltaic depositional environment. However, the lack of interdistributary deltaic facies in the shales between the branches suggests that the Jackpile was deposited far from the sea. More likely the sand body was deposited in an area where broad alluvial plains and belt deposits formed and coalesced, and where distributary and tributary branching of the belt sands occurred (Potter, 1962, fig. 13). The branching may have resulted from periodic channel breakthrough and alluviation on a broad plain, such as occurs within the Mississippi alluvial valley. The original Jackpile sediments probably spread over a far greater area than we now see, for pre-Dakota erosion has removed an unknown amount of the unit.

A broad shallow northeast-trending syncline in the Laguna area probably received more sediments than the bordering areas throughout Morrison time. The unconformable relations between Morrison and Dakota rocks indicate that the Jackpile is partly localized within a broad syncline of post-Morrison, pre-Dakota age; the fact that the Jackpile sandstone also thickens within this syncline, by intertonguing with the Brushy Basin, suggests that the syncline was growing during Jackpile and late Brushy Basin times. That the aggregate thickness of the three members of the Morrison also tends to increase toward the thickest parts of the Jackpile sandstone body (pl. 1) suggests that the syncline was also growing during earlier Morrison sedimentation. Possibly the slowly meandering streams that deposited much of the Brushy Basin flowed in this broad depression. After rejuvenation in the source area, coarser Jackpile sediments were deposited by faster flowing streams that followed the same trough, and the flood plain gradually became broader. Whether or not downwarping continued after Jackpile sedimentation is not known; however, the truncating angular unconformity at the base of the overlying Dakota sandstone indicates an unknown amount of erosion followed by renewed sedimentation.

DAKOTA SANDSTONE

The Dakota Sandstone, of Early and Late Cretaceous age, unconformably overlies the rocks of Jurassic age throughout the Laguna district. The formation ranges from less than 5 feet to more than 100 feet in thickness and is composed principally of black carbonaceous shale and resistant strata of sandstone. The sandstone of the Dakota caps many buttes and mesas or forms prominent benches below the less resistant Mancos Shale. In places coarse sandstone and quartz conglomerate beds are present at the base of the Dakota Sandstone and fill broad scours as much as 20 feet deep in the underlying Morrison Formation. In many areas, however, black shale rests directly on the Morrison. In the northeastern part of the area, where the formation is locally composed wholly of black shale, the Dakota shale is distinguishable from the overlying Mancos Shale only by slight differences in bedding and by the slightly darker color of the Dakota shale.

The name Dakota Sandstone has been applied consistently (except by Young, 1960) to the lowermost strata of Cretaceous age that unconformably rest on the Jurassic and older strata in northwest New Mexico. Dane (1960, p. 48 and fig. 2) reported that on the east and south sides of Mount Taylor the name Dakota has been applied only to a lower tongue of what has been called Dakota to the northeast. On the west side of the Nacimiento Mountains, the name is applied to a carbonaceous shale and coal unit plus a widespread overlying sandstone unit and a discontinuous underlying sandstone unit. Southward the upper sandstone unit pinches out, the carbonaceous shale unit becomes part of the Mancos Shale, and the lower sandstone unit extends through most of the Laguna district and carries the name Dakota (Dane, 1960, fig. 2). Cobban and Reeside (1952, chart 10b) showed the Dakota Sandstone of New Mexico as the lowermost unit of Late Cretaceous age. Dane (1959, p. 90) reported the occurrence of *Halymenites major* Lesquereaux in an exposure of the basal part of the Dakota Sandstone 4 miles northwest of Acoma and stated that this fossil is supposedly restricted to marine rocks, especially sandstones not older than Late Cretaceous. In the Gallup area, however, Dane and Bachman (1957a, p. 97) pointed out that the Dakota Sandstone may be partly of Early Cretaceous age, as well as of Late Cretaceous age.

In the Laguna district the Dakota is thickest on Mesa Gigante (fig. 1, GQ–212) and thinnest in the western and northeastern parts of the district. Channeling of basal coarse sandstone beds into the Morrison Formation accounts for local thickening of as much as 20 feet but does not account for the major regional variations. An upper bed of sandstone forms a good mapping horizon only locally. Possibly the Dakota Sandstone thins by loss of sandstone strata at its top and intertongues with the overlying Mancos Shale.

Typically the sandstone of the Dakota forms prominent benches and vertical cliffs. In places there are as many as four sandstone layers separated by friable siltstone and black shale layers. The sandstone is mostly shades of tan and orange but is locally white. Dark-brown and black manganese and iron stain is common on weathered surfaces.

Most of the sandstone is fine to medium grained, well sorted, and solidly cemented with silica, rarely with calcite. Well-sorted angular to rounded quartz grains form 75–80 percent of the rock. Feldspar grains make up a trace to 2 percent of the rock, and microcline is more abundant than plagioclase. Sparse chert, quartzite, and solidly cemented siltstone fragments are also present. Sparse accessory detrital minerals are zircon, partly altered magnetite and ilmenite(?), apatite, tourmaline, and biotite. Limonite is abundant in the interstices and accounts for the orange and brown hues of the rock. The conglomerate near the base of the unit contains pebbles and sparse cobbles of quartz, chert, and well-cemented quartz sandstone and is cemented by quartz and calcite. The sandstone and conglomerate strata near the base of the Dakota typically have small- to medium-scale trough and planar wedge cross-lamination sets. The sandstone near the top of the unit is typically thinly even bedded and is locally cross-laminated in small-scale sets.

The black shale is commonly thinly interstratified with siltstone and fine-grained sandstone. In many areas, as at the Jackpile mine, a thin bed of fissile black shale marks the base of the unit. Pyrite commonly forms thin films along joints and paper-thin discontinuous laminations parallel to the fissility. At the Jackpile mine, and probably elsewhere, the black shale contains abundant minute rounded white blebs of a waxy substance.

MANCOS SHALE AND MESAVERDE GROUP

The Upper Cretaceous strata, including the thin Dakota Sandstone, have a total exposed thickness of about 2,300 feet, but they once formed a cover perhaps twice this thick over the region. The upper part of this section is best exposed along Mesa Chivato, on the northwest side of the area (fig. 1, GQ–207, 209) and the lower part is exposed over broad areas in lower mesas and buttes south and east of Mesa Chivato. As amply described by Sears, Hunt, and Hendricks (1941) and by Pike (1947), the Mancos Shale and Mesaverde Group intertongue over a broad area and represent alternating marine transgressions and regressions. In this report these two units are described under a single heading because the area of intertonguing relations is much larger than the Laguna district, so that parts of the Mancos Shale are exposed far above the base of the Mesaverde Group. In the Laguna area the Upper Cretaceous deposits form a simple succession, and no one unit is known to wedge out within the area.

The Mesaverde Group, whose lowermost unit is the Gallup Sandstone, overlies most of the Mancos Shale but includes the Mulatto and Satan Tongues of the Mancos well above its base. These tongues thicken and converge northeastward with the main body of Mancos Shale, and they pinch out southwestward (Sears and others, 1941, pl. 26; Pike, 1947, pl. 12).

Both the Mancos and Mesaverde once had formational status (Sears and others, 1941; Pike, 1947), but the Mesaverde has since been given group status and its individual formations named (Beaumont and others, 1956). The stratigraphic nomenclature used here is that used in reports by Dane and Bachman (1957a, b), Dane, Bachman, and Reeside (1957), and Dane (1959, 1960).

The major stratigraphic units of the intertonguing Mesaverde Group and Mancos Shale above the main body of Mancos are, in ascending order, the Gallup Sandstone, the Dilco Coal Member of the Crevasse Canyon Formation, the Mulatto Tongue of the Mancos Shale, the Dalton Sandstone and Gibson Coal Members of the Crevasse Canyon Formation, the Hosta Tongue of the Point Lookout Sandstone, the Satan Tongue of the Mancos Shale, and the Point Lookout Sandstone. The Mancos Shale beneath the Gallup Sandstone is divided into seven mappable units—a lower part consisting of six alternating units of shale and sandstone overlain by a thick body of shale. The three sandstone units in the lower part of the Mancos extend across the Laguna district. Following Herrick's (1900) original account, Dane (1959) applied the name Tres Hermanos only to the second, or middle, of the three prominent sandstone units. For simplicity in this report, the three sandstone units are called the lower, middle, and upper sandstone units of the lower part of the Mancos Shale.

Lower part of Mancos Shale

The three sandstone and intervening shale units of the lower part of the Mancos Shale aggregate about 350 feet in thickness. Typically the upper contact of each sandstone unit is sharp; the overlying shale unit is readily eroded, so that the sandstone forms prominent topographic benches and cliffs. In contrast, the lower contact of each sandstone unit is gradational; well-cemented fine-grained sandstone grades downward into friable siltstone, and thence into shale.

The lower sandstone unit forms a prominent yellowish-gray to pale-yellowish-brown topographic bench. It is typically about 20 feet thick and thinly bedded to massive and contains a few thin beds of siltstone and shale. It is fine- to medium-grained fairly well sorted orthoquartzite to subarkose. It contains as much as 70 percent quartz and 7 percent feldspar, plus small amounts of chert and polycrystalline quartz. Accessory minerals are opaques, rounded zircon, tourmaline, and staurolite. The rock is cemented mainly by calcite and partly by clay.

The middle sandstone unit, called the Tres Hermanos Sandstone Member of the Mancos in nearby areas, is the most extensive of the three sandstones. It extends far northeast of the Laguna district (Hunt, 1936, p. 43) and is the approximate age equivalent of the Greenhorn Limestone in Kansas (Dane, 1959, p. 89). In the Laguna district it is 25–30 feet thick and is typically divided in the middle by a thin siltstone or calcarenite bed which causes the unit to erode to a characteristic double bench. The most striking feature of this unit is the abundant dark-brown-weathering calcareous concretions, some of which are several feet in diameter.

The middle sandstone unit is grayish orange, yellowish gray, or pale yellowish brown and is typically thinly to thickly even bedded and is locally medium-scale cross-stratified. The rock is fine- to medium-grained well-sorted orthoquartzite to subarkose. Quartz composes an average of 70 percent of the rock; feldspar, most of which is partly altered, composes about 2 percent; and chert composes about 1 percent. Fragments of quartzite, shale, and siltstone are present but sparse. Accessory minerals are zircon, opaques, sphene, and leucoxene.

The upper sandstone unit is the thickest of the three in most of the area. It is 35–60 feet thick and is separated from the middle unit by 100–150 feet of shale and siltstone. In many places it forms high cliffs, and its gradation at the base to siltstone and shale can easily be observed. The sandstone is grayish orange to yellowish gray on weathered surfaces and slightly lighter on fresh surfaces. It is flat bedded and ranges from thin to thick bedded. The coarsest material, near the top of the unit, is fine to medium grained, well sorted, and fairly well cemented. Quartz is the main constituent, but some altered feldspar and abundantly disseminated black accessory detrital grains are visible in hand specimens.

The shale units between the three sandstone units are various shades of gray, and the lowermost darkens downward to nearly black. The basal, black shale is similar to that in the Dakota, and where sandstone is absent the contact between Dakota and Mancos strata is gradational. In most areas the top of the uppermost quartz sandstone bed of the Dakota is chosen as the contact between the two formations. The shale between the three sandstone units of the lower part of the Mancos Shale is laminated to thin bedded and is interbedded with thin beds of siltstone and limestone.

Main body of Mancos Shale

The main body of the Mancos Shale, which lies above the three sandstone units, is about 750 feet thick and forms steep, commonly rubble-covered slopes on the east side of Mesa Chivato (fig. 1, GQ–207, 209). For lack of good exposures, this unit was not measured in the field. The shale is various shades of gray and contains a few strata of yellowish-gray or grayish-orange sandstone. The sandstone strata are sharply bounded at their top by shale, and they grade downward to siltstone and shale. They may be equivalent to the tongues of Gallup Sandstone described by Dane (1960). The lower part of the main body of shale is wavy laminated to thin bedded, calcareous, and limonite stained along bedding, and it contains thin limestone beds.

Gallup Sandstone

The Gallup Sandstone, the lowest unit of the Mesaverde Group, forms a prominent bench on the south and east sides of Mesa Chivato (fig. 1, GQ–207, 209). Only the upper member of the Gallup Sandstone—the Gallego Sandstone Member (Dane, 1960, fig. 2; Dane and others, 1957, fig. 4)—was mapped in the Laguna district.

The Gallup Sandstone of the Laguna district is about 80 feet thick. In most places it is very pale orange to grayish orange, but locally it is stained darker by hydrous iron oxides. In the northeastern part of the area, the upper part of the unit is nearly white and has a thin limonite zone at the top; here, the lower 25 feet of the unit forms a vertical cliff, whereas the upper part has eroded to a steep slope having rounded forms and a peculiar polygonal jointing, much as shown by Sears, Hunt, and Hendricks (1941, pl. 29*B*). The sandstone is fine grained, moderately well sorted and poorly to well cemented with quartz, and it contains abundant feldspar and some mica flakes. Concretions of hematite and limonite after pyrite are locally abundant, and fresh pyrite has been found in a carbonaceous zone near the base of the unit. The lower part of the unit is thinly to thickly even bedded; the upper part is cross-stratified. The cross-stratification is planar and forms sets 1–5 feet thick.

Dilco Coal Member of Crevasse Canyon Formation

The Dilco Coal Member forms a ribbed slope that recedes from the cliffs of the underlying Gallup Sandstone, and in most areas it is largely covered with rubble. In the Laguna district the unit is composed of interbedded sandstone, siltstone, and shale; a short distance south and west of the district, however, the unit includes some coal (Sears and others, 1941, pl. 26, measured sections 27, 28). The Dilco is about 85 feet thick in the district, but to the north it thins and disappears (Sears and others, 1941, pl. 26).

The interbedded sandstone and shale or siltstone strata range from about 2 to 13 feet in thickness. Shale strata tend to be thickest near the base of the unit, but the proportion of sand to shale or siltstone strata for the whole unit is about 1:1. The sandstone is many shades of orange and light brown, fine to very fine grained, firmly calcite cemented, and flat bedded; locally it contains thin limonitic layers and flecks of carbonaceous material. The siltstone is grayish orange to very pale orange, friable to well cemented with calcite, and laminated to massive. The shale is grayish brown (5YR 5/2), laminated, fissile, and, locally, iron stained.

Mulatto Tongue of Mancos Shale

The Mulatto Tongue ranges from about 320 to 380 feet in thickness and averages about 350 feet thick. Far north of the district it thickens and merges with the main body of the Mancos Shale (Sears and others, 1941, pl. 26). Exposures are sparse in the Laguna district, for the unit typically forms a rubble-covered slope. The unit includes a few sandstone strata, and these have a sharp upper contact and a gradational lower contact. In Seboyeta Canyon (fig. 1, GQ–207) the graded shale-sandstone sequence is repeated three times—in the lower 65 feet of the unit, in the middle 155 feet, and in the upper 130 feet. In the lower part, fissile olive-gray shale grades upward to yellowish-gray very fine grained sandstone that is well cemented with calcite and forms a subdued bench. In the middle part, interbedded olive-gray shale and yellowish-gray siltstone grade upward to very pale orange very fine grained sandstone that forms a second subdued bench. In the upper part, friable very pale orange to pale-yellowish-brown siltstone grades upward to yellowish-gray very fine grained variably cemented sandstone; a fairly well cemented zone forms a small bench in the middle of the upper sandstone part.

Dalton Sandstone Member of Crevasse Canyon Formation

The Dalton Sandstone Member is about 125 feet thick and is expressed topographically as two prominent sandstone benches separated by a siltstone slope. In Seboyeta Canyon (fig. 1, GQ–207) the upper and lower sandstone beds are 62 and 18 feet thick, respectively, and are separated by 43 feet of poorly exposed slope-forming siltstone. The lower sandstone is grayish orange to yellowish gray, fine grained, well cemented, and laminated to thin bedded. It grades downward into less well cemented very fine grained sandstone in the upper part of the Mulatto Tongue of the Mancos Shale. The upper sandstone is moderate orange pink to very pale orange, fine to very fine grained, moderately well cemented, and massive to faintly stratified; near the top it becomes fine to medium grained and less well cemented.

Gibson Coal Member of Crevasse Canyon Formation

The Gibson Coal Member, which in past years has been mined for coal at several small adits in Bibo and Seboyeta Canyons, is about 290 feet thick and forms slopes with small benches. Exposures are poor, however, and typically rubble covered. The unit is composed mostly of interstratified sandstone, siltstone, and shale; but in a section measured in Seboyeta Canyon, thin beds of coal were found in zones about 130, 155, 170, and 200 feet above the base of the unit. The sandstone, which forms beds as much as 15 feet thick, is typically yellowish gray to grayish orange, fine grained, and generally poorly cemented; some sandstone beds show small-scale planar cross-stratification. The shale is largely dark colored and probably carbonaceous and is fissile; in places it is laminated.

Hosta Tongue of Point Lookout Sandstone

The Hosta Tongue, which ranges from 90 to 115 feet in thickness, is exposed near Seboyeta, where it forms a prominent topographic bench. The lower 70 feet or so of the unit is entirely sandstone, whereas the upper 20 feet or more is sandstone and shale in alternating thin to thick beds that probably reflect the intertonguing contact between the Hosta and Satan Tongues. The main mass of sandstone is pale olive to very pale orange, fine to medium grained, well sorted, and moderately well cemented. Most of the unit is thinly even bedded, but cross-stratification is present in small- to medium-scale planar sets. The shale of the upper part of the unit is dark gray and is interstratified with fine- to medium-grained evenly stratified and cross-stratified sandstone that is much like that of the main mass.

Satan Tongue of Mancos Shale

The Satan Tongue, which is less than 50 feet thick, is exposed near Seboyeta (fig. 1, GQ–207). Sears, Hunt, and Hendricks (1941, pl. 26) did not trace this unit as far south as Seboyeta Canyon, but a few exposures a short distance beneath the basalt rim of Mesa Chivato indicate that it is present. The Satan Tongue is composed of black to light-gray and brownish-gray siltstone and shale in beds about 2 feet thick.

Point Lookout Sandstone

The Point Lookout Sandstone is the uppermost stratigraphic unit of Mesozoic age exposed in the area. Its top is not exposed, but at least 120 feet of its lower strata is exposed locally. This may be almost the true thickness, inasmuch as the unit forms a prominent topographic bench and the slopes above it are less steep and rubble covered. The Point Lookout Sandstone is grayish orange to very pale orange, fine to medium grained, poorly sorted in its coarser parts, and fairly well cemented. Planar medium-scale cross-stratification is locally conspicuous.

Origin of Cretaceous deposits

The thick intertonguing sequence of Mancos and Mesaverde strata was deposited during a series of transgressions and regressions of a sea in Late Cretaceous time. The thick shale deposits of the Mancos and the relatively thin sandstone deposits near the base of that unit formed in the neritic and littoral marine zones, whereas the varied deposits of the Mesaverde Group accumulated under littoral, estuarine, paludal, fluvial, and possibly lagoonal and deltaic conditions (Pike, 1947, p. 15). Shorelines advanced generally from northeast to southwest (Pike, 1947, p. 7), and sediments were derived from a landmass to the southwest. Sears, Hunt, and Hendricks (1941) and Pike (1947) fully described the processes of transgression and regression; so these processes are not discussed here. These authors believed that all the deposits accumulated in a gently subsiding basin and that the formation of transgressive and regressive deposits depended upon the relative rates of subsidence and sedimentation. When subsidence predominated, the sea transgressed; when sedimentation prevailed, the sea regressed (Sears and others, 1941, p. 104; Pike, 1947, p. 15).

The Dakota Sandstone represents the first major transgression in Late Cretaceous time. Thin fluvial sands and then swamp and estuarine deposits accumulated as inundation progressed; these, in turn, were buried in most places by littoral sands and, finally, by neritic shale of the Mancos. Except during three partial regressions, probably only to the littoral zone in the Laguna area, neritic conditions prevailed throughout Mancos deposition. The three partial regressions are represented by the three sandstone units in the lower part of the Mancos.

The Gallup Sandstone represents the first major regression in the Laguna district, probably to near-shore and beach deposition. The interstratified sandstone, siltstone, and shale deposits of the Dilco Coal Member of the Crevasse Canyon Formation probably represent near-shore (both landward and seaward) deposition during the readvance of the Mancos sea; the coal deposits south of the area formed under paludal conditions. The Mulatto Tongue of the Mancos Shale then formed under neritic conditions. The Dalton Sandstone Member of the Crevasse Canyon Formation represents the second major regression, after which this unit was buried by the thick partly paludal deposits of the Gibson Coal Member of Crevasse Canyon Formation. The Hosta and the thin Satan Tongues of the Mancos Shale represent the final transgression, after which these units were buried by the regressive Point Lookout Sandstone. Thick continental deposits of the Mesaverde Group and marine deposits of the Upper Cretaceous Lewis Shale undoubtedly also accumulated in the Laguna district, but the record has been destroyed by erosion.

IGNEOUS ROCKS

The Laguna district is on the east side of the Mount Taylor volcanic field, a northeast-trending belt of basaltic cones, plugs, and flows centering at Mount Taylor. Mount Taylor itself is a large deeply dissected stratified volcano of acidic to intermediate composition (Hunt, 1938). The east side of Mount Taylor extends into the west side of the mapped area (fig. 1, GQ–207), where interstratified acidic pyroclastic deposits and olivine basalt flows form the cap on Mesa Chivato. Many younger flows also cap lower erosion surfaces, and some are near the level of the Rio San Jose. Diabase sills and dikes are abundant in the district, and a dike of monchiquite (a lamprophyre composed of pyroxene and olivine crystals in a groundmass of analcime) is exposed about 1 mile southwest of the Sandy mine (fig. 1, GQ–354).

AGE

The oldest basalt flows of the district form the top of Mesa Chivato, where they overlie tilted and folded Cretaceous strata with marked angular unconformity. Probably correlative with this erosion surface in Mesa Chivato is the so-called Ortiz surface, which truncates deformed strata of the Santa Fe Group in the Rio Grande depression. As the Ortiz surface is probably late Pliocene or Pleistocene in age (Bryan and McCann, 1936, 1938; Wright, 1946), the basalts on Mesa Chivato are probably the same age or younger. Hunt (1938, p. 65) suggested that the basalts erupted "soon after the pediment was formed, because the smooth surface beveling resistant sandstone and easily eroded shale would not otherwise be preserved." When the basalts erupted however, the surface may have been partly dissected, for the east rim of Canyon Diablo (fig. 1, GQ–209) is 200–300 feet lower than the main surface but is capped by basalt similar to the second flow on Mesa Chivato.

Fossils at two localities on top of the fourth flow (QTb_4) corroborate the suggested Pliocene or Pleistocene age for the older flows. One locality is near the south end of Mesa Chivato (fig. 1, GQ–207), where a bed of white limestone about 2 feet thick between the fourth and fifth flows contains abundant fresh-water mollusks. Dwight W. Taylor of the U.S. Geological Survey identified the following:

Fresh-water clam:
- *Pisidium casertanum* (Poli)

Fresh-water snails:
- *Fossaria abrussa* (Say)
- *Gyraulus parvus* (Say)
- *Physa*

Land snails:
- *Pupilla*
- *Vertigo*
- cf. *Succinea*

The other locality is on an erosional relict of Mesa Chivato in the northwest corner of the Mesita quadrangle (fig. 1, GQ–210) where a fossiliferous limestone bed fills a broad depression. Taylor identified the following from this locality.

Fresh-water clam:
- *Pisidium casertanum* (Poli)

Fresh-water snails:
- *Stagnicola palustris* (Muller)
- *Fossaria abrussa* (Say)
- *Gyraulus parvus* (Say)
- *Physa*
- *Ferrissi*

Land snails:
- *Pupilla*
- *Vallonia*

According to Taylor (written commun., 1958), these two assemblages are probably Pliocene or Pleistocene in age; the few identifiable species do not permit a more precise age assignment. The limestone at both localities probably represents deposition in shallow ponds that filled local depressions in the basalt.

Most basalt flows on Mesa Chivato were extruded from vents and fissures after the Mount Taylor volcano became quiescent, but two are known to predate at least the latest eruptions. Of 11 recognized basalt flows on Mesa Chivato, the upper 7 overlap or intertongue with an alluvial cone built eastward from Mount Taylor, the lower 4 are buried by this cone, and the lower 2 are overlain by more than 100 feet of air-dropped ash and lapilli tuff (pl. 2). Closer to the center of Mount Taylor, the oldest flows may have been buried by more than 1,000 feet of pyroclastics. Near the east side of the Mount Taylor amphitheater (Hunt, 1938, p. 65), a plug of olivine basalt, petrographically similar to the second flow on Mesa Chivato, intrudes Cretaceous sedimentary strata. Evidently this plug was buried by a considerable thickness of pyroclastics and was later exhumed during the erosional breaching of Mount Taylor. These relations indicate that at least two basalt flows were extruded while the volcano was active, and that the upper nine flows on Mesa Chivato were extruded probably shortly after the volcano became quiescent and while a large alluvial cone grew eastward from it.

Several subsequent basalt flows were extruded on successively lower and younger erosion surfaces (pl. 2). The two flows on Clay Mesa and the cone from which they flowed (QTb_{12}, QTb_{13}) overlie the Wheat Mountain erosion surface, which was formed 200 feet below the basalt-capped Mesa Chivato erosion surface; two flows (pl. 2, Qb_2; fig. 1, GQ–354, Qb_3) are on or near the present level of erosion. The flow labeled Qb_2 is believed to be older than Qb_3 because it has been partly eroded by the Rio San Jose, and it is more completely buried by alluvial and eolian sands than Qb_3.

The great amount of erosion below the level of Mesa Chivato suggests that the flows on the high erosion surfaces, such as the Wheat Mountain and Mesa Chivato surfaces (pl. 2), are latest Tertiary or possibly early Pleistocene in age, and those that are on or near the present level of erosion are Quaternary in age.

The diabase sills and dikes were probably emplaced in late Tertiary time after structural tilting at the margin of the San Juan Basin, before the extrusion of the basalt flows, and during the period of fracturing that accompanied tectonic activity in the Rio Grande depression. As described later, most of the sills are confined to a thin zone that cuts subhorizontally across tilted strata, suggesting that emplacement postdated tilting. The Dough Mountain plug (fig. 1, GQ–354), which is composed of basalt similar to that of the second oldest flow on Mesa Chivato, contains angular inclusions of diabase. The absence of olivine in the diabase and its presence in all the basalts (table 3) further suggests that the diabase is not related to the basalt. The relations between dikes, sills, joints, and faults, described later, indicate that fracturing overlapped the emplacement of diabase in time. Fracturing, in turn, is inferred to have accompanied late Tertiary tectonic activity in the Rio Grande depression.

The monchiquite dike intrudes a diabase sill, and it probably also transects a fault that cuts the same sill.

DIABASE

As can be seen on plate 4, the diabase dikes strike north to north-northwest, and most of them dip steeply west or east; a few exposed about 2 miles west of Mesita dip east or west at angles as low as 25°. The dikes are as much as 5 miles long and rarely are more than 10 feet thick. Many dikes have remarkably consistent strike and dip, although locally they may deflect into the flat bedding of the country rocks. Their contacts are marked by chill zones a few inches thick that are extremely tough and resistant to erosion, whereas the central, coarser parts are typically friable and easily eroded. Though small displacements across dikes are common, there is no evidence that dikes were intruded along preexisting faults or that faults follow preexisting dikes.

In many places, high-angle dikes deflect into nearly horizontal sills, which elsewhere are deflected downward to form other dikes. (Though a sill by definition is conformable to the country rocks, in this report the term is applied to sheetlike intrusives that are nearly flat-lying and generally conformable but locally break across the stratification.)

Diabase sills seem to be most abundant in the vicinity of the Sandy mine (fig. 1, GQ–354, 210), but they are also widely distributed in other parts of the Laguna district, and they may extend beneath large areas. The sills range in thickness from less than 1 foot to slightly more than 80 feet; the thickest sill occurs east of the Sandy mine area. Most appear to be confined to a

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single subhorizontal zone that rises stratigraphically northward and westward from Triassic through Jurassic and into Cretaceous strata. Because these strata dip gently northward, the sills tend to maintain an altitude of about 5,700–6,200 feet. Available drill data support these relations, for diabase was found only at an altitude of 5,976 feet in DDH–111 (1,129 ft deep), at the Jackpile mine.

The dimensional uniformity of a sill apparently reflects the character of the sedimentary rock it cuts. Sills in the Todilto Formation and Dakota Sandstone are extensive and relatively uniform in thickness, reflecting the well-stratified character of the rocks, whereas sills in the Entrada Sandstone and Jackpile sandstone are deflected by vagaries of stratification and commonly crosscut the units.

An elongate diabase laccolith about 150 feet thick and 1,000 feet wide is exposed about 1½ miles southwest of Mesita (fig. 1, GQ–210), where its crest forms a north-trending ridge nearly 2,000 feet long. The base of the laccolith almost conformably overlies the Entrada Sandstone and the lower part of the Todilto Formation, and its crest is overlain by warped strata of the Summerville Formation. Large tabular inclusions of all three formations have been seen in the diabase. The laccolith thins eastward and westward to a prominent sill; to the west this sill is deflected upward into a dike that cuts sharply across the Summerville Formation and Bluff Sandstone.

Inclusions in the sills and dikes are few and are locally derived. Most could be fit neatly into their original place at the bottom or top of a sill, and they apparently dropped or floated into the diabase magma after it had come to rest. In places limestone slabs have been peeled and bent along the contact of a sill.

PETROGRAPHY

The bulk of the diabase probably has a mineral composition that is typical of diabase in many parts of the world, but most specimens are too punky and altered to warrant detailed work. The least altered specimens contain about 60 percent plagioclase, 30 percent augite, and 10 percent magnetite and small amounts of apatite, zircon, and sphene. Such rocks are ophitic or subophitic, having anhedral augite filling the interstices between randomly oriented laths of plagioclase. The plagioclase is fresh and forms euhedral laths 1–2 mm long that are weakly zoned from calcic andesine probably to middle labradorite; some laths show a gridwork of combined albite, carlsbad, and pericline twins. The augite, which embays the plagioclase and locally forms rods that cut across several laths, is light gray to pale brownish gray and very weakly pleochroic where fresh, but much is partly altered to a reddish-brown or greenish-brown fine-grained micaceous material. Some of this material is biotite that is strongly pleochroic and has strong birefringence, but some is probably chlorite. Magnetite is abundant as disseminated small octahedral crystals and anhedral grains. Apatite forms small rods and fibers. Olivine is conspicuously absent, so that the diabase contrasts with olivine basalt flows. No alteration products of olivine were seen.

One or more layers of lighter colored more resistant rock are common in the thicker sills. The layers are about 2 feet thick and grade into the more typical, punky diabase. The lighter colored rock is similar in texture and mineralogy to the more typical diabase, except that the plagioclase laths are partly altered to a very fine grained material, probably epidote or zoisite, and most of the identifiable plagioclase is nearly pure albite to oligoclase, with a few relicts of andesine to labradorite. The laths show strong normal zoning, and albite locally embays more calcic plagioclase along cleavage traces. Augite is similar in habit and appearance to that in the punky diabase, except that locally along cleavage traces it is replaced by tremolite. Biotite, in ragged to subhedral golden-brown to reddish-brown flakes and books, is probably an alteration product of augite and tremolite.

Aplite sills about an inch thick and having the composition of sodic diorite to quartz diorite form a small percentage of a thick diabase sill a short distance east of the Sandy mine. These sills have sharp contacts and follow nearly flat-lying longitudinal joints in the diabase. None have been found extending into the country rock. The aplite is light gray, fine grained, and equigranular and is composed of about 80–90 percent plagioclase feldspar; 0–15 percent quartz; 5–10 percent magnetite, amphibole, biotite, microcline, and augite; and trace amounts of apatite, sphene, and zircon. Plagioclase, which forms blocky subhedral complexly twinned tabular crystals as much as 1 mm long, is altered but is identifiable as albite and possibly locally as oligoclase. Microcline occurs along albite boundaries and locally embays albite locally along cleavages. Quartz is anhedral and fills interstices between plagioclase laths. Amphibole, as anhedral to euhedral blades and needles, is mostly brown hornblende, but locally it is colorless tremolite(?) or a blue amphibole variety. Dark-reddish-brown to yellow-brown biotite forms sparse euhedral to subhedral books and fine-grained aggregates; locally it has been replaced by albite along cleavages or has been altered from other dark silicates. Magnetite is octahedral and is commonly distributed in trains that form thin dark streaks on the rock surface. Apatite, the most abundant accessory mineral, forms euhedral rods and fibers. Sphene forms anhedral grains in the interstices between feldspar crystals, and zircon forms small subhedral crystals.

A vuggy elliptical pegmatitic body about 2 feet thick and 5 feet wide is exposed near the top of a 75-foot-thick diabase sill a short distance east of the Sandy mine. Its contacts are gradational. Most of the body is an extremely vuggy mass of albite plates as much as 1 cm long. Many of the vugs contain feltlike masses and druses of thin tremolite needles as long as 1 cm. Apatite forms abundant euhedral crystals as much as 1 cm across and 2 cm long in the vugs. Small octahedra of magnetite are abundant in some vugs.

METAMORPHIC EFFECTS

Diabase has metamorphosed the country rock at many places and appears to have pyritized sandstone in wide areas. Expectably, the effects are most pronounced where relatively thick sills cut the calcite-cemented Entrada Sandstone and the Todilto Formation, as in the vicinity of the Sandy mine. Where a sill about 75 feet thick cuts the Entrada Sandstone a short distance east of the Sandy mine, the sandstone is recrystallized for more than 10 feet above and below the sill, and bleached for at least 30 feet above the sill and an unknown distance below the sill. A short distance south of the Sandy mine, folded limestone that lies above a 20-foot-thick sill contains metamorphic garnet and biotite in a zone about 8 feet thick. Metamorphic minerals have also been found to depths of at least 5 feet below thick sills. Thin dikes and sills in the Jackpile mine and that vicinity apparently produced only minor contact-metamorphic effects.

Garnet, the most widespread and abundant metamorphic mineral, is mostly andradite-grossularite (identified by spectrographic analysis and X-ray patterns). The garnet, which may be brown, amber, pale orange, pale green, or colorless, forms auhedral-dodecahedral crystals and granular aggregates in limestone and calcareous sandstone. Many garnet crystals are zoned, with darker colors at the core.

Goldmanite, a vanadium-rich garnet, has been identified as a constituent of a metamorphosed uranium-vanadium deposit in the Sandy mine (Moench, 1962a; Moench and Meyrowitz, 1964). There it is present as minute clear dark-greenish-amber euhedral to anhedral grains embedded in interstitial vanadium clay in dark-gray vanadium-rich Entrada Sandstone. It probably formed by a reaction involving calcite and vanadium clay.

Other metamorphic minerals that are associated with the diabase, but not with the uranium-vanadium deposits, are idocrase, diopside, plagioclase, wollastonite, and micaceous minerals. Idocrase occurs locally as poikilitic crystals as large as 1 cm that include smaller garnet crystals and other materials. Diopside occurs as blocky but ragged crystals, as radiating rods, and as granular aggregates. Plagioclase, commonly intimately intergrown with garnet, idocrase, and diopside, is neither twinned nor noticeably zoned and ranges in composition from albite probably to labradorite; the most calcic plagioclase was found at sill contacts. Wollastonite occurs locally along dike or sill contacts; it is fibrous or bladed and forms white, radiating "sunbursts" on the contacts. Chlorite and small amounts of muscovite and ragged fine-grained biotite occur adjacent to sills and dikes in the Jackpile mine. Fine-grained chlorite also occurs in Bluff Sandstone adjacent to a dike on the southwest side of Mesa Gigante. There it forms both minute olive flakes oriented normal to the surface of sand grains, and aggregates in interstices.

In prospect Pit III of the Sandy mine, small tabular masses of pyrrhotite occur along bedding planes of a garnetiferous calc-silicate rock that was originally limestone; pyrrhotite is interstitial to garnet and other constituents and is partly replaced by hematite. A small metamorphosed uranium-vanadium deposit about 200 feet north of Pit I also contains pyrrhotite, mostly altered to hematite, in a thin layer cut by veins of calcite and euhedral crystals of green garnet. The pyrrhotite probably formed from pyrite by loss of sulfur during metamorphism.

The Bluff Sandstone, the Entrada Sandstone, and parts of the Summerville Formation, where adjacent to diabase, have been altered from red to light tan (fig. 7). The red colors, viewed in thin section, are caused by hematite dust on sand grains. Such hematite dust is

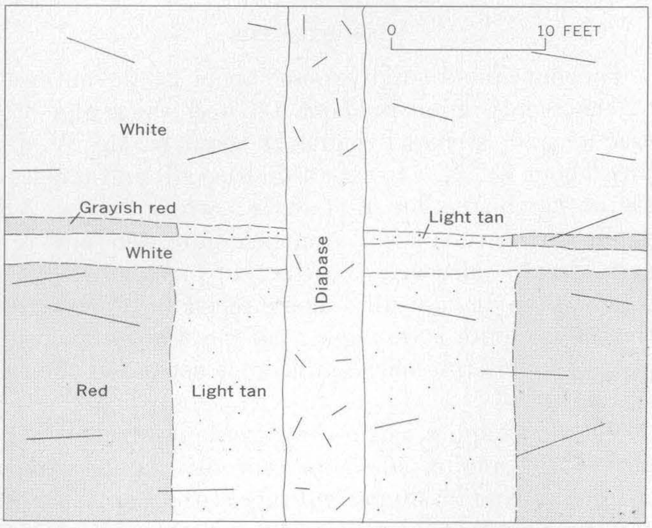


FIGURE 7.—Color differences in crossbedded Entrada Sandstone cut by diabase.

absent in altered sandstone which, where unweathered, contains discrete pyrite grains and 2-inch concretions of pyrite. Detrital magnetite has been altered to pyrite; and ilmenite, to leucoxene. At the surface the pyrite weathers to limonite.

MODE OF INTRUSION

The diabase sills and dikes interconnect without cutting one another; emplacement in a single episode is thus indicated. The conspicuous sparseness of foreign inclusions in the diabase suggests that it was emplaced slowly and passively. If the flow had been more rapid, a greater abundance of wallrock inclusions would be expected, and small inclusions would be expected a considerable distance from their source. Instead, inclusions are of the rocks exposed directly above or below a sill, and the place of origin of many can be found.

The presence of sills between the dikes and the fact that the sills are locally much thicker than the dikes suggest some sort of lifting action. If, for example, several dikes extended to the surface, when still fluid they would tend to lift the masses of sedimentary strata between them, provided the specific gravity of the magma was greater than that of the country rock. If the magma is assumed to have a specific gravity of nearly three, the intervening blocks of relatively less dense sedimentary strata would tend to float, and the magma could flow passively along flat-lying fractures. The thickness of a sill would then increase as the overlying block was lifted higher. Although the sills are mostly conformable in detail, they are mostly confined to a thin subhorizontal zone that cuts across the gently tilted strata. This relation suggests that emplacement was somehow controlled by a nearly flat lying surface of roughly uniform overburden.

MONCHIQUITE

The monchiquite dike exposed about 1 mile southwest of the Sandy mine is about 1½ feet thick and 3500 feet long; it strikes irregularly about N. 55° W. and dips about 75° N. It cuts a diabase sill and crosses a set of north-striking high-angle normal faults. The faults do not displace the monchiquite dike and presumably are older than the dike, but farther south they displace the diabase sill. These relations indicate that the monchiquite is younger than the diabase and suggest that perhaps considerable time separated the two intrusions.

The monchiquite, a dense black vesicular rock, is about 50 percent augite, 10–15 percent olivine, 10 percent magnetite, and 25–30 percent interstitial analcime containing abundant microlites of augite, hornblende, and biotite. Some vesicles are filled with colorless analcime; others are lined with brown opal and filled with either analcime or calcite; and still others are filled with calcite alone. The augite is light gray and forms radiating aggregates of subhedral prisms as much as half a millimeter long. Olivine forms blocky euhedral crystals as much as 1 mm across, and magnetite forms minute disseminated euhedral octahedra. The interstitial analcime and that in the vesicles is colorless and isotropic to weakly birefringent. The microlitic hornblende is strongly pleochroic from colorless to moderate brown; microlitic biotite is pleochroic from colorless to dark reddish brown.

ERUPTIVE ROCKS OF MOUNT TAYLOR

As shown by Hunt (1938, pl. 7), rhyolite, trachyte, and latite are exposed on the floor and walls of the large amphitheater eroded into the Mount Taylor stratified volcano. These rocks are overlain by flows and some tuffs of porphyritic andesite, which form most of the outer flanks of the mountain. A large alluvial cone composed of boulders of volcanic materials mantles the east side of the Mount Taylor volcano and extends eastward into the Seboyeta quadrangle. These coarse alluvial gravels, however, may form only a thin veneer over a thick mass of air-dropped pyroclastic material. The aggregate thickness of alluvial and pyroclastic(?) deposits may be as much as 500 feet in the northwest corner of the Seboyeta quadrangle. In addition, finer grained volcanic gravels and possibly some air-dropped tuffs are interstratified with the olivine basalt flows on Mesa Chivato. Because Mesa Chivato slopes away from Mount Taylor, these alluvial materials undobtedly came from Mount Taylor.

A single exposure about 95 feet thick of largely air-dropped tuff (pl. 2; fig. 1, GQ–207) is part of a tuff unit that overlies two flows (QTb_1 and QTb_2). The upper 25 feet of the unit is mostly stratified gravel composed of rounded pebbles, cobbles, and boulders of porphyritic rock, but it has a pumice–lapilli-tuff bed near the top. The lower 95 feet is very thick bedded punky tuff that contains randomly oriented books of biotite, tabular crystals of feldspar, small crystals of green pyroxene, tabular rock fragments, and small volcanic bombs. Feldspar in the lower part of the tuff is sanidine; that in the upper part is largely sodic oligoclase. The tuff has a crude polygonal jointing that may have formed by shrinkage during cooling.

BASALT FLOWS

Eleven stratigraphically distinct basaltic flows or groups of flows were mapped on Mesa Chivato; other flows were mapped on lower erosion surfaces; and two were mapped near the present drainage level (pl. 2). The distribution and petrographic character of the flows and one plug are summarized in table 3. All the flows have similar composition and contain plagioclase, augite, olivine, and magnetite and (or) ilmenite as their main constituents. The plagioclase ranges mostly from calcic andesine to labradorite; sparse late albite is present locally. For convenience, all the rocks are called olivine basalt, even though the average composition of the plagioclase may not be quite calcic enough for this classification.

Many of the flows can be correlated on the basis of megascopic appearance, and the second (QTb_2), fourth (QTb_4), and ninth (QTb_9) flows are stratigraphic markers which permit recognition of other flows that are interstratified with them and that are also distinguished by minor petrographic differences. Still others—such as the seventh (QTb_7) flow on Mesa Chivato, the basalt of the Cebolleta Canyon plug (Qb_1), the flow near Laguna (Qb_2), and the basaltic rocks in plugs on Mesa Chivato and on younger surfaces—are distinctive in type but are not sufficiently widespread to be stratigraphic markers.

VOLCANIC NECKS AND CONES

Many small volcanic cones rise a few tens of feet to more than 200 feet from the surface of Mesa Chivato, and many necks protrude above the lower country to the east and south. As noted by Dutton (1885, p. 167), most of these necks are erosional remnants of conduits that fed some of the basaltic flows on Mesa Chivato. Dutton (1885, p. 166–179) and Johnson (1907) described many necks a short distance north of the district, and Hunt (1938, p. 67–71) described many necks in the region, including a few in the Laguna district.

The volcanic cones on Mesa Chivato were the source of some flows that are exposed nearby. Most of the cones rise less than 200 feet above the mesa and have been considerably eroded. Craters have been removed, and massive basalt is commonly exposed at the top. Fine ash and cinders have also been removed from the flanks, and generally only coarser, fragmental material remains. Evidence of reactivation can be seen in one cone, whose peak is just north of the mapped area (fig. 1, GQ–207); here, basalt of the 2d flow is cut by thin dikes of basalt that resemble that of the 11th flow. One cone, between Bear and Bibo Canyons (fig. 1, GQ–207), contains basalt of the fourth flow at the top and basalt of the second flow at the base, and is one source of possibly many for both rock types.

The volcanic necks differ in size and structure, but most are alike in that they contain masses of breccia and agglomerate cut by dikes or large pipelike masses of basalt.

The peak of Dough Mountain (fig. 1, GQ–354), formed of massive basalt similar to that of the second flow on Mesa Chivato, is a small plug that is elongated east-west and cuts vertically across poorly consolidated breccia. The breccia contains rounded fragments of scoriaceous and massive basalt, and angular to subrounded fragments of sandstone, mudstone, and diabase. Many irregular thin dikes that dip at low angles in various directions are exposed south of the peak.

Seboyeta Peak (fig. 1, GQ–209) is composed largely of breccia that is cut by many basalt dikes. The basalt is similar to that of the second flow on Mesa Chivato except that it contains olivine clots as much as 1 inch long. The breccia contains scoriaceous basalt fragments of the same type, and large and small blocks of Cretaceous sedimentary rocks, some of which are rimmed by scoriaceous basalt. Some dikes have been broken into large slabs, which indicate that late-stage slumping has taken place.

Cerro de Jacobo (fig. 1, GQ–371) is a nearly cylindrical mass of columnar-jointed basalt about 1,200 feet in diameter. The basalt is similar to that of the second flow on Mesa Chivato. The west side of the plug contains a mass of well-stratified basaltic tuff and agglomerate composed of tuff, lapilli, bombs, and sedimentary rocks but no angular fragments of massive basalt. The tuff and agglomerate dips 30°–50° W., away from the center of the neck and is cut on its west side by a dike of massive basalt.

Cerro de Santa Rosa (fig. 1, GQ–371) is a cylindrical mass of basalt about 700 feet across. The basalt is like that of the second flow on Mesa Chivato except that it contains large clots of dunite. Columnar jointing is vertical near the top of the neck but diverges downward. A crescent-shaped mass of stratified scoriaceous tuff, lapilli, bombs, and a few dunite clots is exposed on the northeast side; strata dip about 35° toward the neck. Breccia composed of finely broken Cretaceous sedimentary rock is exposed near the base of the stratified material. The boundary between the stratified pyroclasts and brecciated country rock is gradational and is truncated by massive basalt.

Picacho Peak (fig. 1, GQ–208) is at the center of a dike 1 mile long and as much as 300 feet thick that strikes N. 30° E. and dips steeply west. The dike is composed entirely of basalt similar to that of the second flow on Mesa Chivato. Columnar jointing is nearly vertical near the top of the dike and diverges sharply downward; near the base it is about normal to the walls of the dike and to faint flow layers.

TABLE 3.—*Distribution and petrography of basalt flows and Seboyeta Canyon plug*

Quadrangle (fig. 1)	Symbol on GQ map	Plagioclase	Augite	Olivine	Magnetite	Other minerals	Alteration products	Distinctive features
Flows near the level of Rio San Jose and the Seboyeta Canyon plug								
Dough Mountain (GQ–354); east side.[1]	Qb_3	----------	----------	----------	----------	----------	----------	
Laguna (GQ–208) and Mesita (GQ–210); near Laguna.	Qb_2	Andesine-labradorite in random laths 0.2–0.4 mm long; space between laths incompletely filled with other minerals.	Colorless, interstitial, mostly fine grained; locally as grains 1 mm across that poikilitically include plagioclase laths.	Pale-greenish-gray equant small subhedral crystals.	Fine grained, anhedral, interstitial; apparently subordinate to ilmenite(?).	Abundant ilmenite(?) plates that cut across other minerals.	----------	Much pore space between plagioclase laths; olivine darker than in other basalts; ilmenite(?) more abundant than magnetite.
Seboyeta (GQ–207); plug in Seboyeta Canyon.	Qb_1	Labradorite in small random to subparallel laths and sparse corroded phenocrysts 2 mm across.	Light gray, fine grained, interstitial; also as blocky corroded phenocrysts 5 mm across.	Equant fine-grained crystals and sparse blocky corroded phenocrysts 2 mm across.	Small euhedral crystals and blocky corroded phenocrysts 5 mm across.	Analcime interstitial, and cristobalite in amygdules; inclusions of quartz sand grains, amphibolite (?), and dense igneous rocks.	----------	Augite and magnetite phenocrysts; cristobalite in amygdules; analcime in groundmass. Rock forms thin dikes and sills in plug.
Flows on Wheat Mountain pediment								
Laguna (GQ–208); Wheat Mountain.	QTb_{13}	Andesine-labradorite in random laths 0.3–1.0 mm long; large crystals locally contain vermicular albite-augite intergrowths; sparse interstitial albite.	Purplish brown, fine grained, interstitial.	Equant fine grained subhedral to euhedral crystals.	Small euhedral crystals and sparse phenocrysts about 3 mm across.	Ilmenite(?) plates----	----------	Rock is gray and slightly coarser grained than underlying flow and contains sparse magnetite phenocrysts.
Laguna (GQ–208); flow on Frog and Clay Mesas, sill on side of Clay Mesa.	QTb_{12}	Andesine-labradorite in random laths 0.1–0.5 mm long and sparse blocky corroded unzoned phenocrysts 4 mm across; sparse interstitial albite.	Purplish brown, fine grained, interstitial; locally forms blades parallel to plagioclase laths.	Equant euhedral crystals about 0.1 mm across.	Small euhedral crystals.	----------	Iddingsite after olivine in flow; iddingsite, hematite, and light-brown mica after olivine in sill.	Rock of flow is gray and dense and has sparse plagioclase phenocrysts. Rock of sill is finely vesicular; flow banding is conspicuous near base.
Flows on Mesa Chivato pediment								
Seboyeta (GQ–207); north side.	QTb_{11}	Andesine-labradorite in subparallel laths 0.2 mm long; sparse interstitial albite.	Colorless, fine grained, interstitial.	Equant euhedral crystals 0.1–0.2 mm across.	Small euhedral crystals.	Corroded quartz fragments rimmed with fine-grained augite.	----------	Rock is medium gray and dense; locally has conspicuous flow banding.
Seboyeta (CQ–207); center---	QTb_{10}	Andesine-labradorite in subparallel laths 0.1–0.3 mm long; sparse interstitial albite; labradorite in sparse zoned corroded phenocrysts.	Colorless, fine grained, interstitial; locally forms rods between plagioclase laths.	Equant euhedral crystals mostly 0.1–0.2 mm across, locally 1 mm across.	-----do----------	Corroded quartz sand grains; ilmenite(?) as thin lenses as much as 10 mm long parallel to plagioclase laths.	----------	Sparse rounded plagioclase phenocrysts and ilmenite(?) lenses; faint flow banding.

Seboyeta (GQ-207); center, north, northeast.	QTb_9	Andesine-labradorite in subparallel laths of uniform size in single specimens, but range from 0.1 mm to 0.2 mm long from place to place.	Light gray, anhedral, fine grained.	Abundant equant euhedral to subhedral crystals 0.2-1 mm across; phenocrysts 5 mm across in some specimens.	do	Sparse ilmenite(?) plates.		Olivine particularly abundant, locally forming phenocrysts 5 mm across; flow banding locally conspicuous.
Seboyeta (GQ-207); center, south; and Moquino (GQ-209); northwest.	QTb_8	Andesine-labradorite in subparallel laths 0.3-1.0 mm long; sparse phenocrysts 2-3 mm across with opaque inclusions in ellipsoidal zones.	Purplish gray, anhedral interstitial grains; darker than in other flows.	Equant subhedral crystals, and plates parallel to plagioclase laths.	Small euhedral crystals; forms clots.	Ilmenite(?) plates; corroded grain in clots of olivine crystals.		Conspicuous trachytic texture; deeply colored augite, corroded hypersthene, and sparse phenocrysts of plagioclase.
Moquino (GQ-209); northwest.	QTb_7	Labradorite in subparallel laths 0.1-0.4 mm long.	Light-gray interstitial grains and sparse euhedral blocky crystals 0.2 mm across.	Equant subhedral crystals as much as 0.2 mm across.	Small euhedral crystals.	Hornblende as tan-brown corroded prismatic phenocrysts as much as 10 mm long, 1 mm across.	Opaques and fine-grained transparent material after hornblende.	Sparse hornblende phenocrysts as much as 10 mm long.
Seboyeta (GQ-207); widespread; and Moquino (GQ-209); northwest.	QTb_6	Andesine-labradorite in subparallel laths 0.2-1.5 mm long.	Light brownish gray, anhedral, interstitial; locally poikilitically includes plagioclase laths.	Small equant grains	do	Ilmenite(?) plates	Iddingsite after olivine.	Trachytic texture of subparallel plagioclase laths conspicuous in hand specimens.
Seboyeta (GQ-207); center, west, south.	QTb_5	Andesine-labradorite in laths 0.1-0.4 mm long and very sparse rounded phenocrysts; sparse interstitial albite.	Brownish gray, anhedral, interstitial; locally poikilitically includes plagioclase laths.	do	do	do	do	Most hand specimens contain 2 or 3 rounded plagioclase phenocrysts.
Seboyeta (GQ-207); widespread; and Laguna (GQ-208); northeast.[1]	QTb_4	Andesine-labradorite in zoned phenocrysts 5-10 mm across and laths 0.1-1 mm long; sparse albite along grain boundaries.	Pale gray, interstitial; some blocky grains 1 mm across poikilitically include plagioclase laths.	Equant euhedral to subhedral crystals as much as 2 mm across.	Small euhedral to subhedral crystals.	Ilmenite plates locally abundant; sparse apatite rods.	do	Porphyritic, locally protoclastic; plagioclase phenocrysts form 5-30 percent of rock and are most abundant near top of flows.
Seboyeta (GQ-207); center	QTb_3	Andesine-labradorite in small randomly oriented laths; sparse albite along grain boundaries.	Brownish-gray anhedral grains; locally poikilitically include plagioclase laths.	Small equant grains	Small euhedral crystals.		do	Rock is dark gray and dense.
Seboyeta (GQ-207); widespread.	QTb_2	Andesine-labradorite in subparallel to random laths less than 0.2 mm long; sparse embayed phenocrysts 1 mm across.	Light brownish gray, fine grained, anhedral, interstitial.	Equant subhedral grains 0.1-0.2 mm across.	Small equant grains; finer grained and partly altered in 2-5 mm across spots.		Iddingsite after olivine; hydrous iron oxides and leucoxene after magnetite.	Rock is dark gray and dense and has round light-gray to grayish red spots that are mostly 2 mm across but may be 5 mm across in thick flows.
Seboyeta (GQ-207); west	QTb_1	Andesine-labradorite in subparallel laths 0.2-0.3 mm long; normal zoning; sparse albite along interstices.	Light purplish gray randomly oriented crystals; poikilitically include plagioclase laths.	Equant subhedral grains less than 1 mm across.	Small equant subhedral to euhedral crystals.		Brownish-green micaceous substance after olivine.	Faint gradational horizontal layering and greenish hue in outcrops.

[1] Rock not studied. Photomicrograph by Nichols (1936, fig. 6) shows plagioclase laths, equant olivine, and magnetite(?) grains in a matrix composed of augite and a small amount of glass(?).

The Seboyeta Canyon plug (fig. 1, GQ–207) is a cone-shaped body about 500 feet across composed of interlayered breccia and scoria cut by thin dikes and sills of basalt (fig. 8). On its west side it stands about 60 feet above the alluvium of Seboyeta Canyon; on its east side it is partly buried by colluvium from the higher ground to the east. The breccia and scoria form concentric layers 5–15 feet thick that dip mainly inward at moderate angles to a common center, except on the southwest side (fig. 8), and are cut by thin lenticular sills and two small dikes of olivine basalt (table 3). The breccia is composed of angular blocks of Gallup Sandstone (which is in place to the east a few feet above the plug) as much as 5 feet across, embedded in a friable matrix of more finely broken sedimentary rocks and some scoriaceous basalt. The scoria forms unbroken sill-like bodies that grade to broken scoria with scoria cement, which locally contains much comminuted sand.

The Seboyeta Canyon plug probably formed by one or more violent eruptions. First, a thin veneer of sedimentary cover was blasted and brecciated; this action resulted in the formation of a crater and the ejection of scoriaceous materials. These materials fell back into the crater and formed the inward-dipping layered deposits. The foldlike features may have formed when these materials draped over irregularities in the crater. Later, olivine basalt welled passively up along cracks and contacts. All the plugs in the district apparently formed in the same manner—by a sequence of violent to quiet events. As a column of gas-charged magma approached the surface, the contained gases exerted considerable pressure in the upper part of the column; and when this pressure exceeded the strength of the overburden, an explosive eruption occurred. With the sudden loss of confining pressure, gases came out of solution to some depth in the column and forced out large

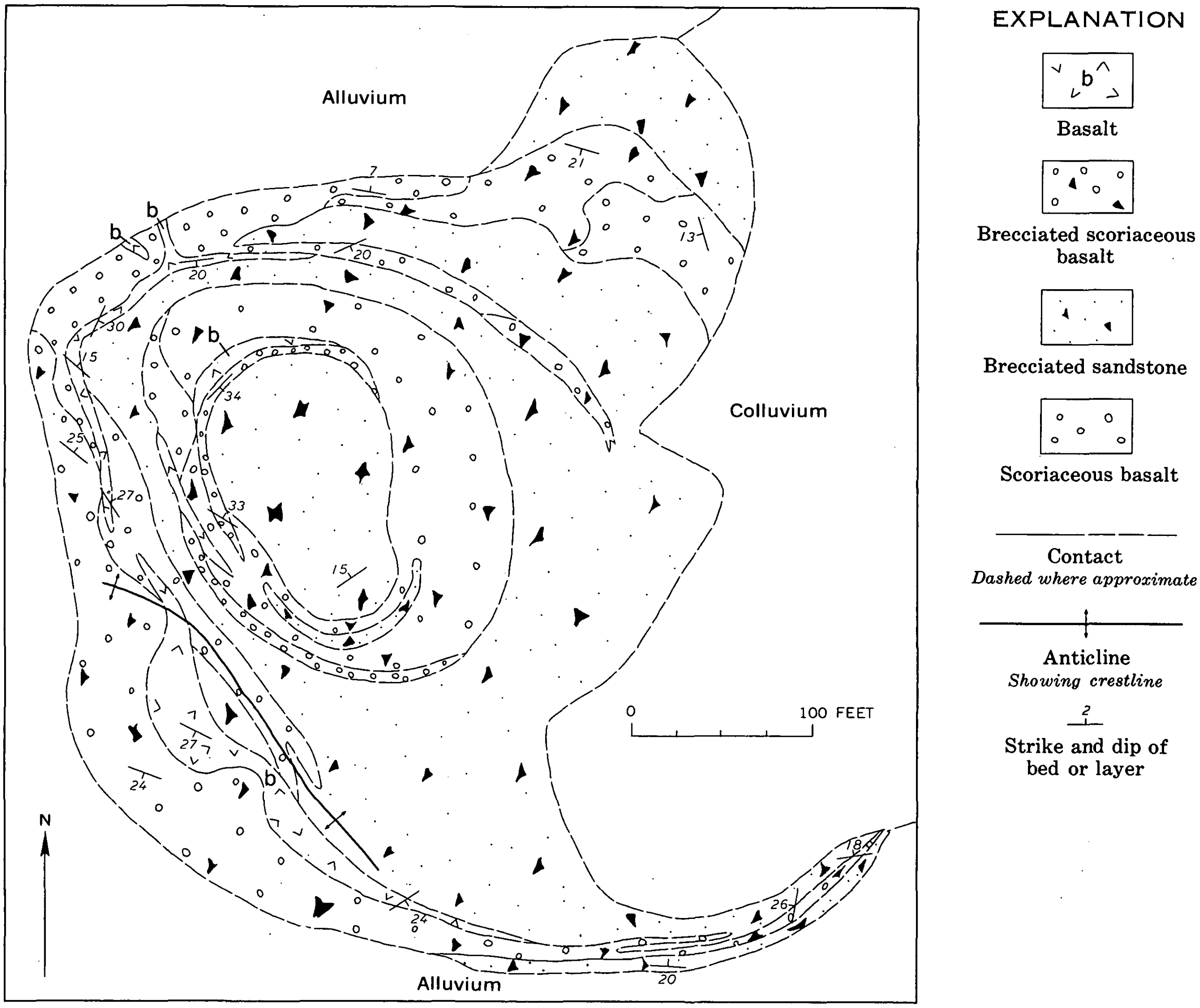


FIGURE 8.—Sketch map of Seboyeta Canyon plug, 1 mile north of Seboyeta village.

amounts of scoriaceous magma. This process continued until the gases were largely released. Later, magma containing less gas quietly welled upward by some other process, perhaps by settling of the crust into the magma chamber.

The process by which magma rises through the crust was discussed by McBirney (1959), who postulated that thermal stresses in roof rocks and wallrocks tend to detach blocks, and that heat loss to the wallrocks sets up convection currents that carry the smaller blocks downward. The magma can then rise in a column by a convection-stoping mechanism. McBirney suggested (1959, p. 446) that the rising magma would tend to produce a cylindrical conduit, because a circular boundary is the most efficient surface of conduction. Picacho peak is a thick dike and is not consistent with this view, but at depth it could be a cylindrical pipe that passes upward into a dike along a preexisting fracture.

SURFICIAL DEPOSITS

Throughout the district local surficial deposits of many types obscure parts of the bedrock geology. All these surficial deposits are the result of Quaternary and Recent erosion and may be considered as material in transit to the Rio Grande drainage. Three general classes of surficial deposits were mapped in the Laguna district: (1) gravels that cover small pediment remnants, (2) colluvial deposits on and near the sides of mesas, and (3) mixed or undifferentiated eolian and alluvial deposits in valley bottoms, on benches, and on mesa tops.

TERRACE GRAVELS

Many small remnants of old pediments are preserved above the present valley floors around the base of Mesa Chivato and locally on the side of the mesa. These remnants are recently dissected flat surfaces that are generally elongate parallel to the present drainage. The surfaces are about 40–200 feet above the nearby drainage level and slope southward to eastward away from Mesa Chivato at grades of 3–5 percent. They are covered by a thin veneer of gravel composed of waterworn pebbles, cobbles, and boulders of igneous rocks. South of Mesa Chivato, and west of its southern extension, the gravel is largely porphyritic igneous rock of intermediate or acidic composition but includes some basalt. East of Mesa Chivato the gravel is largely basalt from that mesa.

COLLUVIAL DEPOSITS

Colluvial deposits cover much of the bedrock on the sides of the mesas, and remnants of colluvial deposits locally extend well into the valley bottoms. Colluvial deposits in the area are of two types: scree and toreva blocks.

Scree mantles the sides of mesas throughout the area. It is composed of creep debris and of talus that forms when the resistant cliff-forming sandstone or basalt is undercut and falls to the slopes below.

A toreva block is a large peripheral segment of a mesa that has slid as a unit and has tilted toward the mesa. Reiche (1937, p. 546), who described this landslide type and named it after its type locality near Toreva, Ariz., noted the many blocks on the sides of mesas near Laguna, N. Mex. Toreva blocks in the Laguna district have formed where resistant sandstone beds overlie thick units of shale—for example, the sandstone units of the Mesaverde Group over the Mancos Shale or the Dakota Sandstone over the Morrison Formation. The largest is half a mile long, parallel to the side of a mesa, and several hundred feet wide. The smallest may be only a few tens of feet long. The most obvious blocks, which show the greatest continuity of resistant layers, are closest to the parent ledge. Successively lower toreva blocks are more disjointed and lose their identity; those at the foot of a mesa are a disintegrated, jumbled mass of colluvium that merges with the alluvial and eolian valley fill. Blocks on the side of a mesa are generally partly buried by alluvial and eolian material, which forms a fairly smooth floor on the back of the block.

Reiche (1937, p. 547–548) suggested that toreva blocks near the type locality probably formed largely in late Pleistocene time, and certainly no less than a thousand years ago. He postulated that they formed during the climatically moist period that characterized the Pleistocene Epoch. The partial burial of the large blocks suggests that their activity has been arrested, or at least slowed.

ALLUVIAL AND EOLIAN DEPOSITS

We made no attempt to distinguish between eolian and alluvial deposits for mapping purposes because such deposits are mixed in most areas and have gradational boundaries. Alluvium predominates near streams and stream beds, whereas locally derived alluvium and eolian deposits are mixed near the margins of valleys and on benches and mesa tops. In many places arroyos cut alluvial material to depths of as much as 30 feet and expose thinly bedded silt and sand. Such deposits probably resulted from sheet wash. About a mile southeast of Laguna, sand dunes cover an area of about 2 square miles. The east, or lee, side of the area is marked by a north-trending bedrock ridge, and directly east of this ridge the sand has drifted to a thickness of perhaps more than 100 feet, probably largely as a result of overgrazing on nearby land. On the south end of

Mesa Gigante, gypsum dunes which have drifted against cliffs of Bluff Sandstone and the Summerville Formation are partly dissected and may have formed during a period when the climate was drier than at present.

STRUCTURAL GEOLOGY

The stratified rocks in most of the Laguna district dip gently northward to westward into the San Juan Basin. Those in the eastern part of the district are deformed by broad folds of low relief and by the north-trending San Ignacio faulted monocline, which forms the west boundary of the Rio Grande depression. The southern part of the district lies in the Acoma sag of Kelley (1955, p. 23, fig. 5), a broad synclinal area between the Lucero uplift, a few miles southeast of the district, and the Zuni uplift, farther west. The district is near the east end of the Chaco slope of Kelley, which is the southern slope of the San Juan Basin. The Nacimiento uplift is about 30 miles northeast of the northern part of the district.

Although deformation of strata in the Laguna district was minor, three general periods of deformation are recognized. The earliest preceded the deposition of the Dakota Sandstone. Though it may have continued into Cretaceous time, it is called the Jurassic deformation because it is known to have partly accompanied Jurassic sedimentation. For convenience, structural features related to this deformation are called Jurassic structural features. The other two deformations followed Cretaceous sedimentation; the first in early Tertiary time and the second in late Tertiary to Quaternary time. They are called the early and late Cenozoic deformations, respectively. For convenience, structural features related to both Cenozoic deformations are called, collectively, Cenozoic structural features, or individually, early Cenozoic and late Cenozoic structural features.

JURASSIC STRUCTURAL FEATURES

Jurassic structural features are a regional northward homoclinal dip on the north flank of the Mogollon Highland, two sets of broad low-amplitude folds, hundreds of sandstone pipes, intraformational faults, and various intraformational features that characterize parts of the Todilto Formation (pl. 3). The regional homoclinal dip was a major controlling feature of Jurassic sedimentation, and the largest east- to northeast-trending folds (the more important of the two sets) influenced sedimentation at least through Morrison time.

REGIONAL HOMOCLINE

The Dakota Sandstone lies with angular unconformity on the Jurassic rocks of the area, and southward it rests on successively older strata. These relations represent a simple erosional planation of successively older north-dipping Jurassic rocks prior to deposition of the Dakota Sandstone. Southward sedimentary changes in the Jurassic rocks indicate that a positive area (the Mogollon Highland of Harshbarger and others, 1957) existed in central and southern New Mexico during Jurassic time. The boundary between this highland and the basin of Jurassic deposition trended west to northwest across central New Mexico probably just a few tens of miles south of the Laguna district, and its effects on sedimentation can be seen in the southward coarsening of the Entrada Sandstone, the pinching of the Todilto Formation, and the coarsening and thinning of the Summerville Formation (Silver, 1948; terminology different from that used this report). Because both the Bluff and Morrison Formations were truncated southward by erosion, the effect of Jurassic tilting on the deposition of these units is not fully understood.

FOLDS

Many folds deform the Jurassic strata of the regional homocline and, to a lesser degree, overlying Dakota Sandstone. The Seama Mesa anticline, whose crestline is immediately south of Seama Mesa and Casa Blanca Mesa (pl. 3), is expressed by a pronounced thinning of the Morrison Formation beneath the Dakota Sandstone and corresponding arching of the underlying Bluff and Summerville Formations (pl. 3, section *B–B′*). Similarly, north-trending folds in Oak Canyon and on the south side of Mesa Gigante (pl. 3, section *A–A′*; fig. 1, GQ–210, 212) are expressed by gentle folding and corresponding thinning and thickening of Jurassic strata below the Dakota Sandstone.

Some folds shown on plate 3, such as the Bell Rock anticline and other folds that pass under the central part of the Mesa Gigante, were not identified in the field but are inferred because of marked changes in thickness of Jurassic strata. Such thickness changes are too great to be attributable to channeling or intertonguing or to relief on the pre-Dakota erosion surface.

Other folds, such as those near the Sandy mine (pl. 3; fig. 1, GQ–354), warp Jurassic strata long distances from exposures of Dakota Sandstone. Such folds are inferred to be of Jurassic age because they are parallel to and have the characteristics of other folds of known Jurassic age.

EAST- TO NORTHEAST-TRENDING FOLDS

Many folds of this set were mapped in the area south of Laguna, where they trend generally east; and some were identified in the Mesa Gigante area, where they trend northeast (pl. 3). Owing to lack of adequate exposure, the folds could not be traced between these two areas; but they are probably parts of the same general set, which apparently swings from a generally east to a northeast trend. The maximum dimensions of folds of this set are not known, but a broad synclinal warp probably conforms to the easterly to northeasterly elongation of the Jackpile sandstone (pl. 3). Such a fold would have sufficient amplitude and breadth to localize the streams that deposited the Jackpile sediments (p. 22) and probably is more than 13 miles wide and several hundred feet deep.

The Seama Mesa and Bell Rock anticlines possibly represent the same structural feature in two separate areas (pl. 3, sections *B–B′*, *C–C′*). North of the crestlines the Morrison Formation thickens from generally less than 200 feet to locally more than 600 feet in the center of the postulated syncline that contains the Jackpile sandstone. South of the crestlines the Jurassic rocks are warped by many east- to northeast-trending folds. Here the Morrison Formation ranges in thickness from less than 50 feet at places along the crestlines to as much as 275 feet along the troughlines. The Alamo Spring syncline and the anticline immediately to the north (exposed southwest of South Butte, pl. 3) are an exceptionally large anticline-syncline pair whose structural relief is about 220 feet in a distance of 0.7 mile. A short distance west of the mapped area the syncline passes under a small mesa capped with Dakota, and there a lens of Morrison as much as 50 feet thick is exposed directly beneath the Dakota Sandstone. The lens of Morrison is not present, however, in two small mesas short distances to the north and south.

The angularity between the beds of the Dakota Sandstone and the underlying formations of Jurassic age indicates that folding took place partly during the interval between Jurassic and Cretaceous sedimentation. That folding was also taking place while the Jurassic sediments accumulated is indicated by stratigraphic relations within the Morrison Formation (see p. 22), by thickening of Todilto limestone within the syncline (described later), and by the localization of belts of sandstone pipes along the folds (pl. 3).

The east- to northeast-trending set of Jurassic folds appears to be a local manifestation of a major structural trend in northwest New Mexico. Because these folds are subparallel to the Jurassic Mogollon Highland, to the south, they may have formed as a result of differential movements between the sinking basin of sedimentation to the north and the rising landmass to the south. Whether this movement was compressive folding or vertical adjustments of large blocks cannot be determined from evidence obtained in the Laguna district. There is no known evidence to indicate that any movement occurred before Jurassic time.

NORTH-TRENDING FOLDS

North-trending Jurassic folds are relatively small but pronounced and are particularly well exposed in the south end of Mesa Gigante, and in the vicinity of Oak Canyon (pl. 3). Some of the folds are narrow synclines bounded by monoclines; others are more regularly spaced anticlines and synclines. They are oriented about normal to folds of the east- to northeast-trending set and change trend sympathetically from due north, south of Laguna, to about N. 25° W., in the Mesa Gigante area.

North-trending folds in the south end of Mesa Gigante are grouped into four synclines (pl. 3), the first three of which are shown on section *A–A′* (pl. 3). Syncline 1 is about 2,500–3,000 feet broad and, as judged from the thickening of Jurassic rocks, drops as much as 80 feet from its borders to its axis. Some of the relief in syncline 1 has been removed by a low-amplitude Cenozoic anticline that is directly superimposed on the Jurassic downwarp. The relief on the Bluff-Morrison contact is about 60 feet on the west side of the syncline and about 40 feet on the east side (pl. 3, section *A–A′*).

Syncline 2 is covered by the upper part of the Bluff Sandstone and by the Dakota Sandstone; the lower part of the Bluff thickens markedly in the syncline (pl. 3, section *A–A′*). The central part of the syncline is grabenlike and has numerous high-angle faults, too small to show in the section, stepped downward toward its center. These faults locally contain sandstone dikes and apparently formed while the sediments were largely unconsolidated; the top of many faults is truncated and overlain by less deformed Bluff strata. Thus, syncline 2 formed during early Bluff sedimentation. Inadequate exposure prevents determination of whether the syncline formed by removal of underlying Todilto gypsum, by deformation of the whole underlying section, or by a combination of both processes.

Syncline 3 is complicated by minor flexures on its west flank and by a low-amplitude anticline a short distance farther west (pl. 3, section *A–A′*). As determined from variations in thickness of the Morrison Formation, the syncline is about 2,500 feet broad and has a maximum relief of about 80 feet. Relief on the Todilto limestone a short distance to the south is considerably less, and the greater structural relief of the higher strata may be attributed to thinning of Todilto gypsum in the syncline.

The north-trending folds in the Oak Canyon area (pl. 3) are simple anticlines and synclines. Isopach data for the Jackpile sandstone (pl. 3) indicate a maximum relief of about 85 feet in a horizontal distance of slightly less than 2,000 feet.

The origin of the north-trending folds is enigmatic.

The fact that the trends of the folds vary sympathetically about at right angles to the trends of the east-trending folds suggests that the two sets are somehow related. Stratigraphic evidence likewise indicates that they formed within the same interval of time. Although the north-trending folds shown on plate 3 appear to be concentrated in the central and southeastern parts of the district, there is no conclusive evidence that they do not occur over much wider areas, and certainly the areas of north- and east-trending folds are not mutually exclusive. Conceivably the two sets of folds may be analogous to metamorphic terranes where small folds at right angles to the major folds are commonly related to the same deformation system (Cloos, 1946, p. 26–29). On the other hand, the stratigraphic record reveals that major north-trending arches and troughs as old as Pennsylvanian are present throughout northwest New Mexico (Read and Wood, 1947; Wood and Northrop, 1946; McKee and others, 1956, pl. 3). Conceivably the north-trending folds formed by the reactivation of these earlier structural features and, so, are unrelated to the formation of the east- to northeast-trending folds, which have no known antecedents.

INTRAFORMATIONAL STRUCTURAL FEATURES IN THE TODILTO FORMATION

The Todilto Formation is characterized internally by innumerable small but intricate folds, thrust faults, joints of various types, and breccia zones. The folds range from minute crenulations, which appear as fine lineations on bedding planes, to structural features that deform an interval of limestone 10–20 feet thick. Some of the largest features deform the underlying Entrada Sandstone; the contact zone between the Todilto and overlying Summerville Formation is commonly intensely deformed. Because all the structural features are best developed in the limestone, they are called intraformational. Their origin depended largely upon the physical behavior of poorly consolidated semiplastic limestone during or shortly after sedimentation.

Folded limestone typically overlies a few feet of nearly undeformed limestone, which in turn rests on the Entrada Sandstone. A typical large fold is shown in figure 9. Note the general lack of deformation in the lower part of the limestone. The structural relief of some folds diminishes gradually downward into undeformed limestone; in such folds slippage took place along many bedding planes, and the amount of slippage increased upward. Many folds bottom abruptly on undeformed or only weakly deformed strata; in such folds slippage took place mainly along a single bedding plane and formed a miniature décollément. Slickenside striae, oriented normal to fold axes, are common on bedding planes and fault surfaces and may be found on bedding planes of seemingly undeformed limestone.

Calcite apparently has been redistributed in various parts of folds. In some folds, radial joints that intersect on an approximately common line about parallel to the axis are healed by coarsely crystallized calcite. In other folds fine-grained massive limestone fills "pressure shadows," particularly along the axis of the fold.

The upper, massive limestone zone in the Todilto commonly is brecciated and mixed with sand from the overlying Summerville Formation. Mixed rocks of this type, as much as several feet thick, appear to be localized near large intraformational folds in the underlying bedded limestone. Fragments have sharp but ragged edges, range from a small fraction of an inch to 1 or 2 feet in diameter, and are firmly cemented by undeformed sandstone or calcite. Both fragments and cementing materials in the breccias appear to be composed of locally derived Todilto and Summerville materials. Most commonly, ragged limestone fragments are embedded in massive sandstone, but sandstone fragments are locally embedded in limestone. Neither substance appears to have been completely solid when the breccia formed. The limestone apparently was crenulated and partly consolidated prior to brecciation, but it was sufficiently plastic in places to incorporate some sand. Sand, which apparently flowed freely between

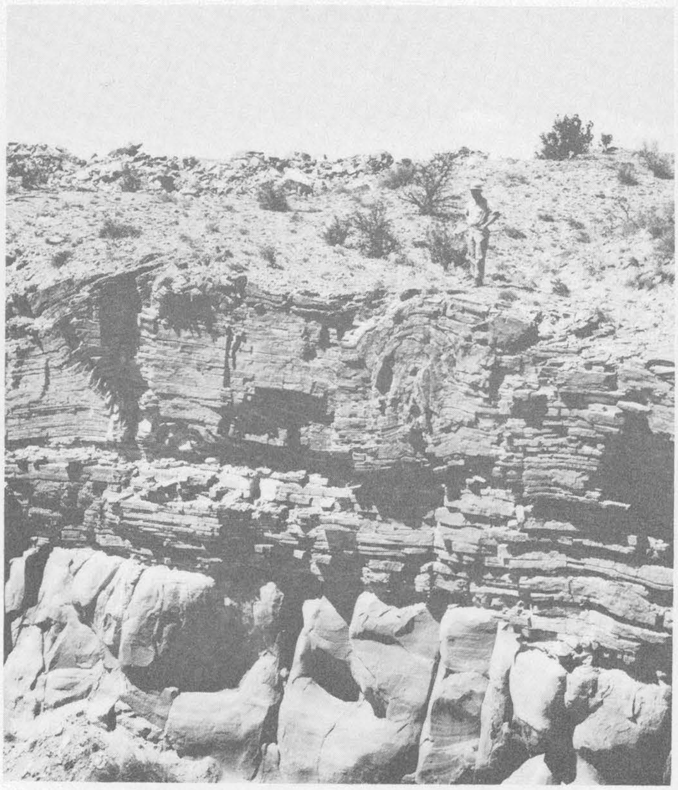


FIGURE 9.—Fold in limestone of the Todilto Formation.

limestone fragments, was largely unconsolidated during deformation.

Small folds are locally confined to units 3 or 4 inches thick in the stratified zone of the limestone, and they are common where the limestone is otherwise undeformed. Concentrically folded laminated limestone is bounded above and below by undeformed laminated limestone, and coarse calcite fills the "pressure shadows" in the crests and troughs.

The axes of most folds are extremely sinuous, and some diverge as much as 90° from their dominant direction, or even double back on themselves. Some folds bifurcate at a low angle, and at places as many as four folds radiate from a common center—plunge away from a single high point.

Though extremely sinuous, the intraformational folds trend chiefly in two directions—east to northeast and slightly west of north—parallel to the two sets of major Jurassic folds. The bearings of all folds measured in the area are represented in compass diagrams on plate 3. In the areas southwest of Mesita (pl. 3), most Jurassic folds trend east, and the strongest maximums in the diagrams parallel that direction; lesser maximums trend north-northwest. In contrast, the largest maximum in the diagram for folds east of Mesita (pl. 3) is parallel to that for the north-northwest-trending Jurassic folds that are well exposed in the area. A small maximum is oriented east-northeast. Because of the extreme sinuosity of many folds these relations are striking. The sinuosity of the fold axes contributes to the broad spread of the maximums, but the presence of the maximums and their relation to the larger folds are unmistakable.

Limestone thickens markedly in the east-trending Jurassic synclines, mainly because of intraformational folding. For example, in an east-trending Jurassic fold with more than 100 feet of relief exposed in the Sandy mine area (fig. 1, GQ–354), the limestone is about 15 feet thick near the fold crest but 30 feet thick in the syncline to the south. The limestone is more than 25 feet thick near the troughline of the Alamo Creek syncline and 10–16 feet thick in the anticline immediately to the north (pl. 3). At both localities the total measured thickness of limestone includes the folded stratified and massive zones. The stratified zone alone is generally about half again as thick in the synclines as in the anticlines, largely because the intraformational folds have greater amplitudes in the synclines. The massive limestone, including mixed breccia and much contorted material, is distinctly more abundant in the synclines.

The large-scale warping that took place during Jurassic sedimentation appears to have induced slumping and sliding of semiconsolidated limestone into the synclines. The apparent lack of intraformational unconformities in the limestone and the fact that the upper part of the Todilto commonly contains intermixed material from the lower part of the Summerville indicate that deformation took place under a cover of Summerville sediments. On the other hand, the evidently plastic, semiconsolidated character of the limestone during deformation suggests that the cover was not thick. Under a probably thin cover, then, plastic limestone apparently slid down the limbs of synclines and piled up near the trough. This sliding took place along well-lubricated bedding planes above the base of the unit; it produced sinuous compressional folds whose axes roughly parallel those of the larger warps, thrust faults where limestone slipped across several strata, and intraformational mixing along the Todilto-Summerville contact.

DOMELIKE FEATURES

The top of the Todilto Formation is an extremely irregular surface. Small hummocks or knolls of massive limestone and associated sandstone are profuse in local areas; some rise as much as 20 feet above the surrounding surface and apparently reflect the true character of the contact zone. The interior of most of these hummocks is not exposed, so the structure and composition of the hummocks is not fully known. Some hummocks may be composed entirely of massive limestone and be merely a pronounced local thickening of the unit. The few exposed interiors consist of a thick lens of gypsiferous sandstone underlain by stratified limestone and overlain peripherally by a thin layer of massive limestone. The sandstone has the aspect of a blister near the top of the limestone. The largest hummock found is 300 feet in diameter and at least 20 feet high. It is breached, and the thin layer of massive limestone upholds a circular ridge that surrounds a topographic basin from which most of the sandstone has been removed. Whether or not the thin cap of massive limestone originally extended completely over the top of the feature cannot be determined from the exposure.

The distribution of the domelike features suggests that they are related to sandstone pipes. Although some are exposed where sandstone pipes are few in the overlying Summerville and Bluff Formations, they appear to be most abundant where the pipes likewise are most numerous. For example, six large domelike features are exposed in a small area near a group of pipes about one-third of a mile west of the Crackpot mine.

INTRAFORMATIONAL FRACTURES

The Summerville, Bluff, and Morrison strata locally contain abundant fractures that formed penecontemporaneously with sedimentation. Such fractures—joints, faults, and a few sandstone dikes—are most abundant where Jurassic folds are most pronounced, and some north-trending folds are also fracture zones.

Many faults terminate and are buried under higher beds of the units they cut; thus, they are clearly penecontemporaneous. Also, the fact that strata in the footwall of a fault in the Summerville Formation (fig. 10) are thinner than equivalent strata in the hanging wall indicates that the fault was active during sedimentation. Similar though smaller faults are locally abundant in the Bluff Sandstone and in sandstone beds of the Morrison Formation. Some of the faults and a few joints contain sandstone dikes as much as half an inch thick that were derived from the sandstone beds the dikes cut; evidently the dikes formed when the sand was unconsolidated.

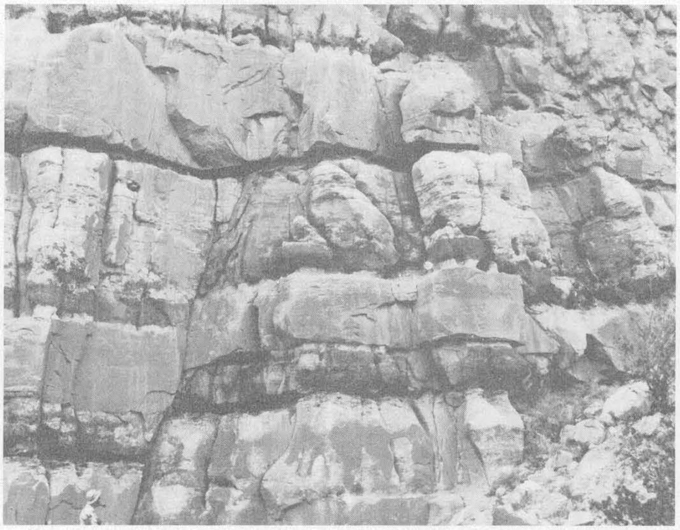


FIGURE 10.—Fault in Summerville Formation.

Intraformational fractures are most abundant where Jurassic folds are most pronounced, and they are not consistently parallel to any Cenozoic fracture set. The two categories of fractures overlap in their orientation, however, and attitude can be used as a diagnostic feature only with caution in small areas of detailed study. Figure 11*A* represents the poles of all penecontemporaneous fractures measured in sandstones of the Summerville, Bluff, and Morrison Formations in the Laguna district. This diagram does not resemble any of the stereodiagrams of joints of two regional fracture systems (pl. 4).

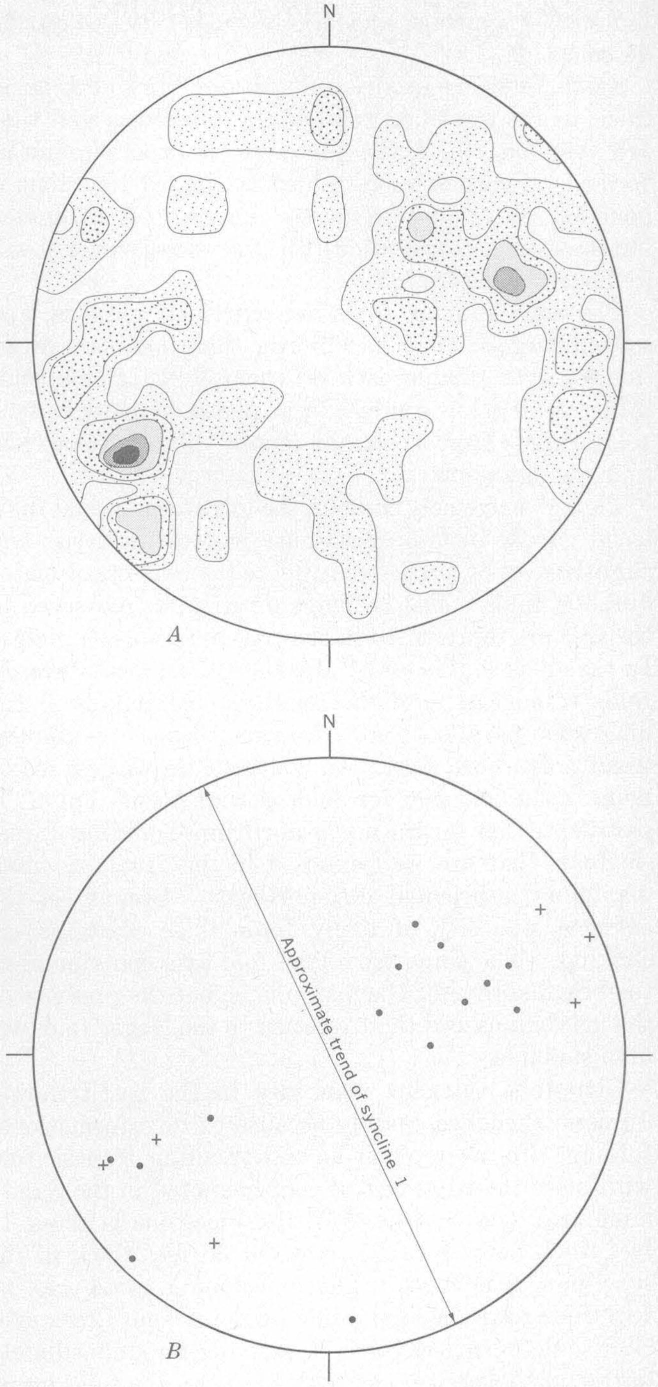


FIGURE 11.—Patterns of penecontemporaneous fractures in sandstones of Summerville, Bluff, and Morrison Formations. *A*, Fractures throughout Laguna district. Poles of 60 fractures plotted on upper hemisphere of Schmidt net. Contour interval 1.7 percent. *B*, Fractures in Bluff Sandstone (•) and sandstone of Morrison Formation (+) measured on sides of Mesa Gigante near syncline 1 (pl. 3). Poles of 22 fractures plotted on upper hemisphere of Schmidt net.

Many small joints and faults occur in syncline 1 in the upper part of the Bluff Sandstone and in the sandstone strata of the Morrison Formation that lie directly above the belt of sandstone pipes (pl. 3). The pipes are buried by the upper part of the Bluff Sandstone, whereas the fractures are exposed above this unit. The attitude of the fractures is shown in figure 11*B;* clearly, most strike about parallel to the axis of the syncline and the belt of sandstone pipes. The faults show normal displacements of a few inches; some are truncated by overlying strata. These fractures appear to have formed in response to downward movements in the structural depressions during sedimentation.

SANDSTONE PIPES

Many hundreds of peculiar collapse structural features, termed "sandstone pipes," are exposed in the Summerville, Bluff, and Morrison Formations (Schlee, 1963). They are nearly vertical cylindrical sand bodies that range from 1 inch to 200 feet in diameter and from 1 foot to possibly as much as 300 feet in height. The crosscutting character and cylindrical form of these and similar structural features in other terranes have provoked controversy for many years, and no widely accepted explanation has yet been proposed. In the Laguna district the pipes appear to be collapse features that formed as the enclosing sediments accumulated. These pipes are of particular geologic interest here because two are known to be mineralized—the Woodrow deposit, which yielded several thousand tons of the richest uranium ore in the district, and a large collapse feature in the Jackpile mine.

DISTRIBUTION

Several hundred sandstone pipes are exposed in the district, mainly south and east of Laguna, where the Summerville Formation and Bluff Sandstone are widely exposed (pl. 3); no doubt many more are buried to the north beneath the thick cover of Cretaceous strata.

All the known pipes are confined to the Summerville, Bluff, and Morrison Formations—a Jurassic interval that totals nearly 1,000 feet in thickness. In general, pipes extend downward from thick sandstone beds into thick units composed mainly of siltstone and mudstone. Two large pipes are known to extend downward from the Jackpile sandstone into the Brushy Basin Member of the Morrison Formation; a few small pipes have been found in the Westwater Canyon Member, and these probably extend downward into the Recapture Member. Most pipes, however, were found in the Bluff Sandstone and the Summerville Formation. In this sequence most large pipes extend downward from about the middle of the Bluff into or through the Summerville, and apparently terminate downward on the Todilto Formation.

Although some pipes appear to be isolated, most are concentrated in groups or belts containing as many as 100 pipes. Most such groups or belts are parallel to both the east- and north-trending sets of Jurassic folds (pl. 3). One belt follows the axial zone of the Alamo Spring syncline (pl. 3), but other belts are on the north- or east-dipping limbs of Jurassic synclines.

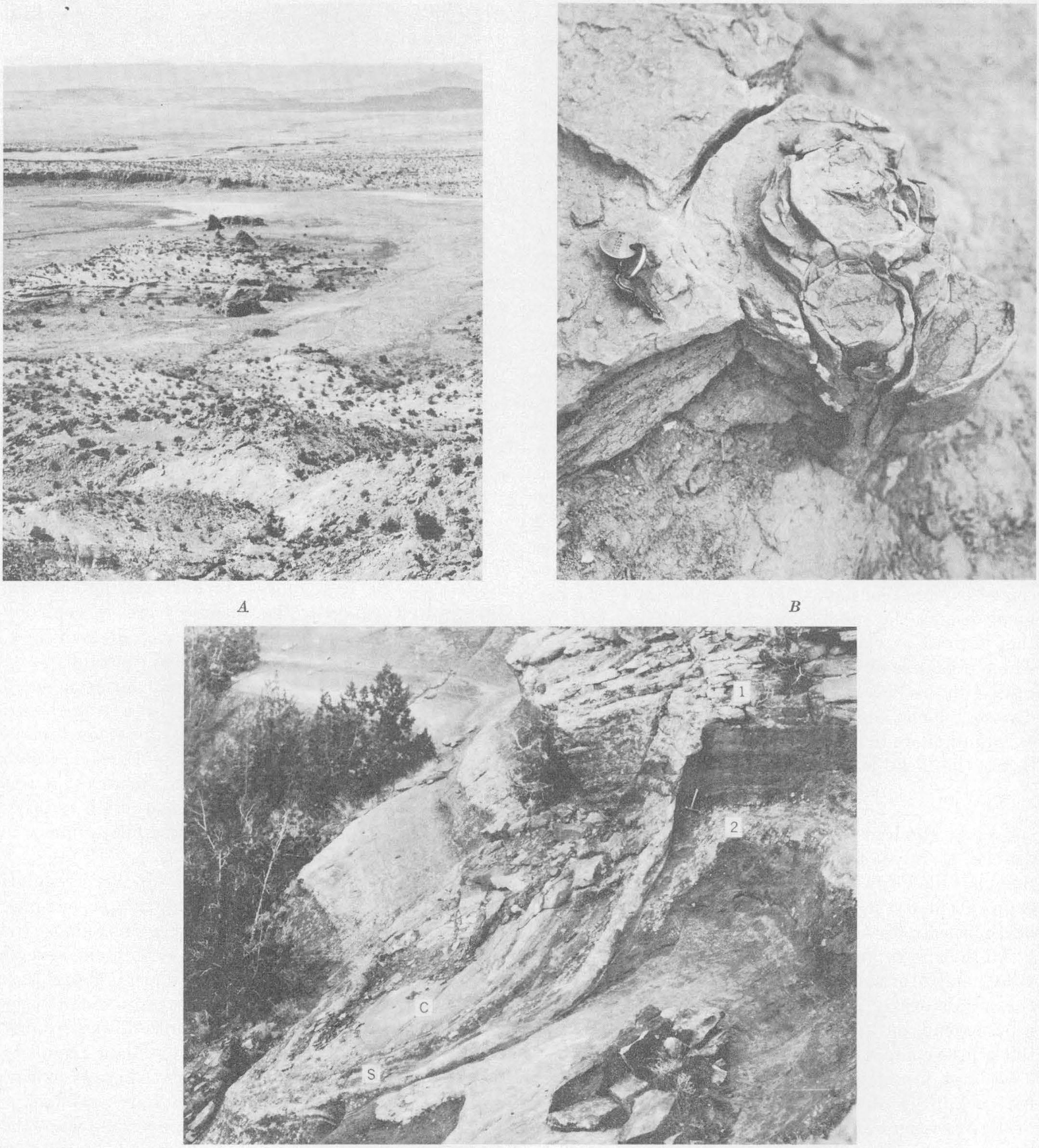
The belt that follows the west limb of syncline 1, on the southwest corner of Mesa Gigante, contains many more pipes than can be shown on plate 3 or on the quadrangle map (Moench and Puffett, 1963b). Many rounded towers and hummocks rise above the exposed Bluff Sandstone and Summerville Formation and the alluvium of the valley bottom (fig. 12*A*). This belt of pipes possibly extends southward under Mesa Gigante, where it is buried by the upper part of the Bluff Sandstone and by the Morrison Formation. To the south it reappears as single pipe.

DESCRIPTION

The most common surface expression of a large pipe is a knobby column of massive sandstone, in places rising more than 20 feet above the surrounding surface. Where well exposed, the massive core is typically bounded by concentric ring faults or ring dikes of sandstone. Rarely, the central part is less resistant to erosion than the surrounding rock and forms a small topographic depression surrounded by a ring-shaped ridge. The outcrop of the Woodrow pipe, a low protrusion above the surrounding surficial debris, is indicated only by discontinuous semiconcentric fractures; it was discovered only because of its extremely high radioactivity. The large pipe in the Jackpile mine was uncovered during mine operations.

The cylindrical form of sandstone pipes is irregular, and many pipes are compound. For example, one pipe may intersect another, so that only a crescent of the older pipe remains; or a pipe may contain several smaller pipes. These relations are shown in figure 12*B*, which illustrates some of the smallest pipes found in the area. Pipes apparently range in width downward, but whether widening or narrowing is dominant cannot be determined from surface exposures. The Woodrow pipe, for which many subsurface data are available, is from 24 to 34 feet in diameter; the upper 50 feet of the pipe plunges about 67° S. 50° E.; below a depth of 50 feet the pipe spirals to a plunge of more than 80° N. 45° E. (Wylie, 1963, p. 177).

The boundaries of most pipes are sharp. They may be marked by a zone of concentric ring faults and ring-shaped sheaths of sandstone or by the sharp contact be-



A *B*

C

FIGURE 12.—Sandstone pipes. *A*, View northward toward sandstone pipes on limb of syncline southwest of Mesa Gigante. Synclinal axis lies to right of pipes. *B*, Closeup of small compound sandstone pipe. *C*, Eroded sandstone pipe. Concentric sandstone sheaths (S) surround massive core (C). Sandstone strata of wallrocks shown by numbers.

tween the massive sandstone column and the surrounding strata. Strata around a pipe may dip inward, toward the pipe, or they may be flat lying. The pipe shown in figure 12*C* has a massive sandstone core of small diameter (C, about 3 ft) bounded by a wide zone of concentric sandstone sheaths (S). The outermost sheath extends downward from the uppermost stratum of light-colored sandstone (1) in the wallrock and truncates the next lower stratum of light-colored sandstone (2). Both strata have been displaced downward toward the pipe by ring faults that are approximately concentric to the pipe.

The core of a pipe may be compact massive sandstone or it may be a compact jumbled mixture of angular to rounded sandstone and mudstone fragments embedded in a massive sandstone matrix. Both the fragments and the sandstone matrix appear to be derived locally. The core of a plug rarely is undeformed, and it appears to have been dropped as a unit from a short distance above (Schlee, 1963, fig. 6).

Where the top of a pipe is exposed, the pipe has obviously been buried by the uppermost sediments that contain it. Small pipes (a foot or less across) are funnel-shaped at the top and are overlain by stratified sandstone which tends to sag slightly over the top of the pipe. Similar relations have been observed at the top of a large pipe in the Bluff Sandstone and of the large pipe that was exposed by mining operations in the Jackpile mine.

Exposures of the base of a pipe are rare. About 3 miles east of Laguna, however, the bottoms of two pipes in the upper part of the Summerville Formation are exposed. Both pipes are underlain by relatively undeformed strata (Schlee, 1963, fig. 4*C*).

Although the full vertical extent of a pipe is nowhere exposed, our observations of the rare exposures of the upper and lower ends of pipes suggest that each pipe extends downward from about the middle of a layer of sandstone into a layer of siltstone or mudstone. Pipes that top in the Jackpile sandstone probably bottom at some level within the Brushy Basin Member; those that top in the Westwater Canyon Member probably bottom within the Recapture Member; and those that top in the Bluff Sandstone probably bottom within or at the base of the Summerville Formation.

Materials within the sandstone pipes evidently moved downward from their place of origin. Strata sag over the tops of pipes, and commonly around their margins, and are displaced downward toward the center by concentric ring faults. Where the tops of pipes are well exposed, much material evidently flowed into the pipe from the surrounding surface. The abundant carbonaceous material in the Jackpile mine must have been drawn into the pipe, as plant material from the surrounding surface, by a rapid downward movement within the pipe. Finally, petrographic evidence suggests that materials that make up the core of a pipe were derived from adjacent or overlying strata (Schlee, 1963, table 1).

It is rarely possible to correlate stratigraphic zones outside a pipe with remnants of stratigraphic zones within a pip. At the Woodrow mine, rocks in the pipe have been dropped 30–45 feet relative to those outside the pipe; the amount of drop differs for each zone correlated (Wylie, 1963, p. 177).

RELATION TO GYPSUM

Neither the areal nor the stratigraphic distribution of sandstone pipes coincides with that of the gypsum unit of the Todilto Formation. For this reason, and also because some pipes do not extend downward to the Todilto, removal of underlying gypsum cannot easily explain the origin of all the pipes. Nevertheless, gypsum is thin or absent near some pipes, so that a local relation between pipes and the removal of gypsum is suggested.

One group of pipes is about one-fourth mile northwest of the Crackpot uranium deposit (pl. 3), a short distance east of a thick unit of gypsum. The gypsum wedges out sharply toward the group of pipes, and, still closer, several domelike lenses of gypsiferous sandstone are exposed.

On the south side of El Rito Mesa, just north of Mesita (fig. 1, GQ–210), gypsum is missing from a zone about 2,000 feet wide above which two pipes are exposed; the pipes are possibly part of a north-trending belt of pipes. On either side of the zone the gypsum is about 60 feet thick. Within the zone gypsum is replaced by a much thinner lens of massive fine-grained yellowish-gray sandstone that contains small fragments of limestone. This sandstone may represent material that was introduced from above through the pipes as the gypsum was removed.

ORIGIN

Sandstone pipes in the Laguna district formed during the accumulation of the uppermost strata that contain them, particularly in areas where gentle penecontemporaneous folding was taking place. The dominant process was evidently one of subsidence of unconsolidated or semiconsolidated sand into mud, for pipes of all sizes appear to be confined to strata in which sandstone overlies mudstone.

In the Laguna district, pipes have been attributed to "penecontemporaneous sag or collapse due to removal of support by flowage or solution of the underlying gypsum" (Mirsky, 1955). Strong support for this process can be seen at El Rito Mesa, north of Mesita, but the facts that some pipes terminate at their lower end well above the gypsum and that the areal distribution of pipes is far greater than the present distribution of gypsum suggest that this was not a major process. Possibly, though, different pipes originated by different processes, and gypsum may formerly have been much more widespread.

Gableman (1957) postulated that most pipes on the Colorado Plateau (including the Laguna district) are cryptovolcanic features that originated from gaseous volcanic explosions. The limited stratigraphic distribution of pipes in the district and the absence of any evidence of explosion or of high temperature alteration in the pipes studied preclude this possibility.

We suggest that the pipes formed by foundering of sand into spring vents during compaction and dewatering of the sediment. At some stage in the accumulation of sand on top of water-saturated mud, the area was deformed; this deformation produced north- and east-trending synclines. The structurally low areas received more sediments than the higher areas; and the resulting greater weight of sediment in the synclines, coupled with spring activity alined along the folds, permitted foundering of sand into spring vents. As the process continued, the sand moved downward and mixed with materials derived from the sides of the vents. The total amount of room required to accommodate the sand was probably considerably less than the volume of the pipe, because the pipes are composed of materials derived from the sides as well as from the top. Room for the sand was probably created by compaction and dewatering of the finer sediment. Where spring activity extended in depth to the Todilto, solution of gypsum unquestionably enchanced the formation of pipes.

Because the bulk density of water-saturated sand is greater than that of water-saturated silt or clay (Emery, 1950), an unstable condition is created whereever a layer of sand is deposited on water-rich mud, especially if the mud is thixotropic. This instability can be responsible for intraformational folds. (Emery, 1950; Kaye and Power, 1954) or for a multitude of subsidence features that characterize interstratified turbidite graywacke and shale. We suspect that this instability coupled with spring activity might also be responsible for sandstone pipes.

Folding and faulting during sedimentation would aid the formation of springs and account for the beltlike distribution of most pipes, for springs are common products of tectonic disturbances. Hobbs (1907, p. 128) described springs and geysers that formed during the New Madrid earthquake; Hobbs (1907, p. 9–10) and Heck (1936) described subsidence craters as much as 100 feet across that formed during another earthquake. The alinement of springs along faults is fairly common.

Creation of space by water loss needs further explanation; some of the larger pipes have a volume in excess of 3.5 million cubic feet, much of which is occupied by introduced sand. Silt and fine sand can yield by "flow failure" (Krynine, 1947, p. 148), during which the sediment undergoes a readjustment of loosely packed grains. The shift toward more dense packing results momentarily in liquefaction of the mass of sediment owing to vibration induced by tectonic disturbance, and momentary liquefaction of thixotropic clays might lead to a similar flow failure. The resulting liquid might easily have been pressed upward and out of the pipe, along whatever channels were available, by the downward-moving sand. Evidence of this upward movement would probably be difficult to find.

CENOZOIC STRUCTURAL FEATURES

Two general stages of deformation probably spanned most of the Tertiary and possibly extended into Recent time. The two stages—early Cenozoic folding followed by late Cenozoic fracturing and uplift—probably overlapped in time. The major structural features of both deformations are shown on plate 4. The San Ignacio faulted monocline, on the east side of the mapped area, marks the boundary between the Colorado Plateau and the Rio Grande depression to the east. Through most of the district the strata dip north to west into the San Juan Basin and are further deformed by domes, basins, north-trending folds, widely scattered north-trending faults of small displacement, and several sets of joints.

The total error in the structure contours drawn on the base of the Dakota Sandstone (pl. 4) may locally exceed the 100-foot contour interval used. The error is probably greatest in the northern part of the district where the Dakota is deeply buried, because the interval to be subtracted from a higher horizon cannot be determined precisely and may be variable. The Dakota ranges from about 5 to more than 100 feet in thickness in the district; where the Dakota is covered, its thickness is assumed on the basis of its thickness in the nearest exposure or drill hole. The method of map compilation, by Kelsh plotter, introduces an additional error of about 20 feet.

FOLDS AND HOMOCLINE

The boundary of the San Juan Basin follows the Madera anticline and its southwest extension, the Madera terrace (pl. 4 Moench and Puffett, 1963a). The east boundary of the basin is fairly well defined, but the southeast boundary is indefinite and arbitrary.

West and northwest of the Madera anticline and terrace the Cretaceous strata slope about 100 feet per mile into the San Juan Basin. This nearly continuous dip is interrupted locally by broad terraces, some of which have slight closure. The 100-foot contour interval on plate 4 reflects only the largest of these terraces, but many smaller terraces exist.

East of the Madera anticline and west of the San Ignacio faulted monocline, the rocks are warped by several broad gentle anticlines, synclines, domes, and basins in a belt about 5 miles wide and 15 miles long (pl. 4). From the crest of the Madera anticline, the strata dip as much as 8° eastward into the Arch Mesa syncline and basin; farther east they rise gently, with some reversals, to a series of anticlines and domes near the east margin of the belt.

The Cretaceous strata rise steeply to the north end of the Lucero uplift, about 13 miles south of Mesa Gigante, where uppermost Permian rocks are exposed at an altitude of about 6,500 feet (Kelley and Wood, 1946, section *B–B′*). If we assume that about 1,300 feet of Chinle and about 650 feet of Jurassic strata once overlay the Permian (Kelley and Wood, 1946, section *A–A′*) the base of the Dakota here would be at an altitude of 8,450 feet, or about 2,000 feet higher than at the south end of Mesa Gigante.

Some Cenozoic folds may be amplifications of older folds. The Madera anticline (pl. 4) is nearly superposed on three areas where the Jackpile sandstone is thin or absent (pl. 3). This zone of thinning is transverse to the elongation and sedimentary trend of the sandstone body and probably represents a broad low-amplitude north-northwest-trending anticline of Jurassic age. The Madera anticline, therefore, is probably a reactivated Jurassic fold.

FRACTURES

The fracture pattern illustrated by means of joint diagrams and mapped faults on plate 4 is perhaps the most striking characteristic of the Cenozoic structural features in the district. It is discussed in detail to give a basis for distinguishing between Jurassic and Cenozoic fractures in uranium deposits, to clarify parts of the geologic history of the district, and to provide a basis for determining the character of stresses to which the area has been subjected. Because the district lies on the boundary between the Colorado Plateau and the Basin and Range province, fractures can be studied in relation to the structural histories of both regions.

FAULTS WEST OF SAN IGNACIO FAULTED MONOCLINE

With the exception of the San Ignacio faulted monocline, faults are widely spaced and of small displacement throughout most of the Laguna district (pl. 4). The faults strike dominantly north to north-northeast and nearly vertical, and most have a normal displacement which nowhere exceeds 50 feet. In the central and western parts of the district, individual faults can rarely be traced more than 2 miles and, commonly, less than 1 mile; farther east, near the San Ignacio faulted monocline, single faults can be traced for as much as about 4 miles. The faults are fairly straight, and at their ends they show no evidence of horse-tailing or feathering out. Fault surfaces are commonly slickensided, and striae are oriented directly downdip; vugs containing calcite, pyrite, or hematite pseudomorphs after pyrite are locally present. Two faults in the southwestern part of the district strike northeast, in contrast with the dominant northerly trend. One is a normal fault that dips 65° S., has an irregular trace, and contains wide vugs filled with abundant calcite. The other is not well exposed.

Hunt (1936, p. 61) noted that at many localities in the Laguna district the downfaulted beds dip into the faults, and that rarely do beds on opposite sides of faults show the expected drag. He reported that other faults fail to disturb the strike and dip of the beds. North-trending faults of the Laguna district especially fit Hunt's description. Much of the displacement on some of these faults, in fact, is attributable to downbending of beds on the downthrown side. If the north-trending faults formed under regional east-west elongation, as postulated in a later section (p. 50); some openings would be equal in width to the heave of the fault. Such openings might be closed by gravitational settling of the hanging wall by amounts that depend on the heave and dip of the faults.

The number of faults having relative displacements down either to the east or to the west is about equal in the southwestern part of the district, and there is little if any structural relief. In the northern and eastern parts of the district, however, faults having displacement in similar directions are distributed in fairly definite zones. Westward from the San Ignacio faulted monocline, in a belt about 4 miles wide that narrows northward, the dominant direction of displacement on the faults is down to the west. West of this belt, on the west side of the La Gotera and Arch Mesa quadrangles, the dominant displacement is down to the east, and farther west the displacement is again down to the west.

Faults west of the San Ignacio faulted monocline may reflect some of the youngest structural activity in the region. High-angle north-trending normal faults cut diabase sills southwest of Mesita, and one such fault cuts a basalt flow on Mesa Chivato. Sills are not known to cut faults, nor do dikes follow faults having more than a few feet of displacement.

SAN IGNACIO FAULTED MONOCLINE

Hunt (1936, p. 64) applied the name San Ignacio monocline to the feature that forms the boundary between the slightly faulted Colorado Plateau to the west and the greatly faulted Rio Grande depression to the east. This structural feature has local monoclinal characteristics, but as a whole it is as much a zone of faults as a monoclinal fold and is called the San Ignacio faulted monocline in this report. It forms the western part of the Puerco fault belt of Kelley (1955), a wide north-trending belt of normal faults connecting the Nacimiento and Lucero uplifts on the north and south, and separating the Colorado Plateau from the deeper parts of the Rio Grande depression. Strata cut by most faults in the Puerco fault belt are downthrown to the west, but because individual blocks tilt eastward, the structural relief across the belt probably does not much exceed 2,500 feet.

On plate 4 many faults in the San Ignacio faulted monocline are shown to cross one another without recognizable horizontal displacement. None of these intersections are well enough exposed to allow determination of which fault is younger. Because all the faults have steep dips and most are probably dip-slip faults, displacements of one fault by another cannot be large.

The San Ignacio faulted monocline is about 30 miles long and ranges in width from a single fault trace to a fault zone as much as 2 miles wide (pl. 4). At its south end it is a single fault on which strata are downthrown more than a thousand feet to the east. This fault probably converges southward with the Correo fault of Kelley and Wood (1946). The southern part of the fault zone shown on plate 4 consists of many straight north-northeast-trending, crudely en echelon faults apparently truncated by arcuate faults that account for much of the displacement across the zone. Here, the strata on the east side of the zone have been dropped as much as 2,200 feet relative to those on the west side. The rocks in this part of the fault zone are mostly tilted eastward, and in places they are step-faulted down to the west, so that the relief across the zone is reduced. The central part of the fault zone is marked by a single fault; northward the zone swings to a north-northwest trend, broadens, and becomes more complex. The northern part of the fault zone is characterized by many en echelon northeast- and east-trending faults interspersed with a few north-trending faults. Though due to more faults, the total displacement across this part of the zone is less than that to the south. Near the north boundary of the quadrangle (Moench, Schlee, and Bryan, 1965), the total displacement is less than 400 feet, much of which is attributable to one reverse fault; a short distance to the north, the fault zone passes into an east-facing monocline having little structural relief.

The dominant displacements across the San Ignacio faulted monocline were probably dip slip. In the southern half of the zone, strata in the tilted fault blocks or slivers strike nearly parallel to the faults; strike-slip components totaling several miles of displacement would be necessary to account for the vertical separations. In the northern part of the zone, the major displacements were probably dip slip, even though slickenside striae are both steep and nearly horizontal; the fault traces are too short for the faults to have had strike-slip components large enough to account for the observed vertical separations.

The San Ignacio faulted monocline probably formed in response to vertical movements—east side down with possibly a small right-lateral component—on a large north-trending high-angle fault at depth. The dominantly vertical movement is indicated by the gross vertical stratigraphic separation across the feature; the right-lateral component is suggested by the crudely en echelon patterns within the faulted monocline. The many faults within the zone across which strata are downthrown to the west may have formed in response to monoclinal bending. This is particularly evident in the southern part of the fault zone (pl. 4); faults increase in number northward, and the displacement of strata down to the west increases with increasing dip to the east.

The possibility that the San Ignacio faulted monocline formed under a regional couple cannot be eliminated. En echelon fracture patterns, which are detectable in parts of the faulted monocline, have been produced experimentally by coupled stress—for example, those produced by Cloos (1955, pl. 2, fig. 2, and pl. 3, figs. 1 and 2). Applied to the Laguna district, the trend of the San Ignacio faulted monocline might be interpreted as one shear direction, and the north-northeast-trending faults, as about normal to the direction of tension in the couple. A right-lateral couple, then, would be oriented slightly west of north, and it would tend to move the area to the east of the faulted monocline south relative to the area to the west. The accompanying folds should trend west-northwest, for the major direction of compression in such a stress system would be oriented north-northeast. North-trending folds about parallel to the shear direction, however, are possible.

JOINTS

Cenozoic joints,[1] which are present throughout the sedimentary strata of the district, are oriented in at least six joint sets.[2] Three joint sets strike nearly north, north-northeast, and north-northwest, respectively, dip steeply to vertically, and appear to form a major joint system [3] that developed in response to late Cenozoic tectonic activity. The three other sets, which strike about at right angles, respectively, to the three sets of the major system and also dip steeply to vertically, are not clearly understood; they may be analogous to the unsystematic cross joints described by Hodgson (1961, p. 13, 18) and have no tectonic significance.

Joints and small faults of widely different ages are present in the district: those that formed during or shortly after Jurassic sedimentation, described previously, and those that formed in Tertiary and possibly Quaternary time. The younger joints are far more abundant, widespread, and persistent in strike and typically have steeper dips than the older, and they are in rocks as young as the late Tertiary(?) diabase.

Observation of the orientation and characteristics of joints—their spacing and smoothness and the presence or absence of mineral matter or slickensides in them—was the primary method of joint study. The fracture pattern in the district shows little regard for topography; the same pattern is obtained near and distant from a mesa rim. To illustrate the orientations of the major joint sets and determine if the less abundant joints of different orientations are systematically oriented, the poles of the joints were plotted on the upper hemisphere of Schmidt equal-area diagrams and contoured (pl. 4) according to the method described by Billings (1954, p. 112–114). Each of the 13 contour diagrams represents an area of fairly homogeneous geologic structure; the outline of each area is shown on the map (pl. 4). The joint diagrams on the map (pl. 4) were derived from the contour diagrams. Each major maximum on the contour diagrams is represented by a strike line, and dips are shown for maximums that are not vertical; the length of the strike line is proportional to the percentage of the maximum. A few short strike lines represent small maximums that are not shown on the contour diagrams, because some contours were omitted to simplify drafting. The amount of data recorded in areas of about equal size differs greatly. The dominant joint sets, however, are sufficiently persistent to be defined by as few as about 40 measurements. Diagram 2 (39 measurements), for example, is consistent with diagrams for nearby areas (74–144 measurements).

One principal set of joints (labeled B on the map in pl. 4) strikes nearly parallel to the north-trending high-angle faults and diabase dikes west of the San Ignacio faulted monocline. Locally, joints of this set have persistent attitudes, as shown by the conspicuous maximums they form in some contour diagrams. From one area to another, however, these joints change in strike from about N. 15° E. to N. 5° W., apparently sympathetically with strike changes of the faults and diabase dikes. This set is not represented in diagrams 8 and 10 (pl. 4).

Joints of the B set are the only ones that commonly contain pyrite veins. Such veins are most abundant in the Bluff Sandstone where it is intruded by many diabase dikes and sills. The veins, which at the surface are composed largely of hematite after cubic pyrite, may be half an inch thick and can be traced horizontally for several tens of feet; their lateral extent, however, may be considerably greater. Concretions of hematite after pyrite as much as 3 inches across are commonly alined along joints of the B set in the same areas. Elsewhere, most of the joint surfaces are thinly coated with iron and manganese stains. Except for local, minor deflections where they intersect stratification, joints of this set are planar or very slightly curved. The trace of a single B joint, as indicated by any of the longer diabase dikes, may be more than 5 miles long.

In many areas the B set approximately bisects the acute angle between two other joint sets (labeled A and C on pl. 4). The A set strikes from about north (diagram 3, pl. 4) to N. 30° W. (diagram 7, pl. 4), and the C set strikes from about N. 10° E. (diagram 7, pl. 4) to N. 50° E. (diagram 3, pl. 4). The A and C sets tend to vary in strike sympathetically with strike variations of the B set, faults, and diabase dikes.

The A and C joints, which more precisely are strike-slip faults of small displacement, commonly exhibit conspicuous horizontally striated slickensides; these features were not seen on joints of any other set. The slickensides are most conspicuous on thin films of white or iron-stained quartz that line the joint surfaces, but they have been seen on joint surfaces that are barren of mineral matter. Slickensides were observed most commonly on A and C joints in the Dakota Sandstone, which is more intensely jointed than most other units, but they have been found on joints in sandstone units throughout the stratigraphic section.

[1] "A joint is a fracture without significant relative displacement of the walls, which is a member of a group of fractures spatially extensive in three dimensions generally, or within the bounds of a given rock body" (Mitcham, 1963, p. 1157); this definition, accepted here, eliminates the many rough and apparently unsystematic fractures that can be found in most outcrops.

[2] A group of subparallel joints.

[3] A group of intersecting genetically related joint sets.

Joint sets labeled A_c, B_c and C_c (pl. 4) are approximately normal in strike to the A, B, and C sets, except in those diagrams where one or more of the latter are not represented. Because the A_c, B_c, and C_c joints tend to rotate sympathetically with strike changes of the other sets, they are probably unsystematic cross joints that are similar to those described by Hodgson (1961, p. 13, 18). They are poorly understood, however, and conceivably may represent an entirely independent joint system with a tectonic significance of its own.

Like the unsystematic cross joints discussed by Hodgson (1961), the A_c, B_c, and C_c joints tend to be arcuate and to have rough, irregular surfaces. Unlike Hodgson's cross joints, however, they may be long and may intersect several joints of the A, B, and C sets. At one locality, horizontally striated A and C joints that strike N. 25° W. and N. 35° E., respectively, are intersected and offset (less than a tenth of an inch) by joints that strike N. 70° E. and N. 75° W., respectively. Offsets along the joints that strike N. 70° E. are right lateral, whereas offsets along the joints that strike N. 75° W. are left lateral.

Joints in the north half of the San Ignacio faulted monocline (diagrams 4 and 5, pl. 4) are not classified, because the fault pattern is too complicated to serve as a guide to joint classification. However, the diagrams, especially diagram 5, suggest that the pattern of A, B, and C joints has swung from a generally north strike west of the faulted monocline to a northeast strike in the faulted monocline. The fault pattern in the south half of the zone is simpler and permits classification of the joints (diagram 6). A few minor sets that defy classification are evident in other diagrams for areas west of the fault zone.

RELATIONS BETWEEN FRACTURES AND LITHOLOGY

In the Laguna district the B joint set exhibits marked changes in attitude from one rock type to another. In relatively strong rocks the joints are about vertical, whereas in weaker rocks they form two inclined sets. In a small area (about 1 sq mi) at the Sandy mine sufficient data were collected to contrast the fracture patterns in two very different rocks—the probably relatively strong Todilto limestone and the relatively weak Entrada Sandstone. The limestone (fig. 13*A*) has a simple joint system consisting of vertical north-south and east-west B and B_c joint sets similar to those indicated in diagram 13 of plate 4. In contrast, the sandstone (fig. 13*B*) contains six well-developed joint sets, all of which dip at abnormally low angles in comparison with joints in the limestone. Further, the B joint set in the limestone appears to separate in the sandstone into two B sets that dip at relatively low angles.

Joint sets in the Dakota Sandstone, a relatively strong unit, and those in the Jackpile sandstone, a relatively weak unit, also contrast. In figure 14, joints measured in the Jackpile sandstone in the open pit of the Jackpile mine are contrasted with joints measured

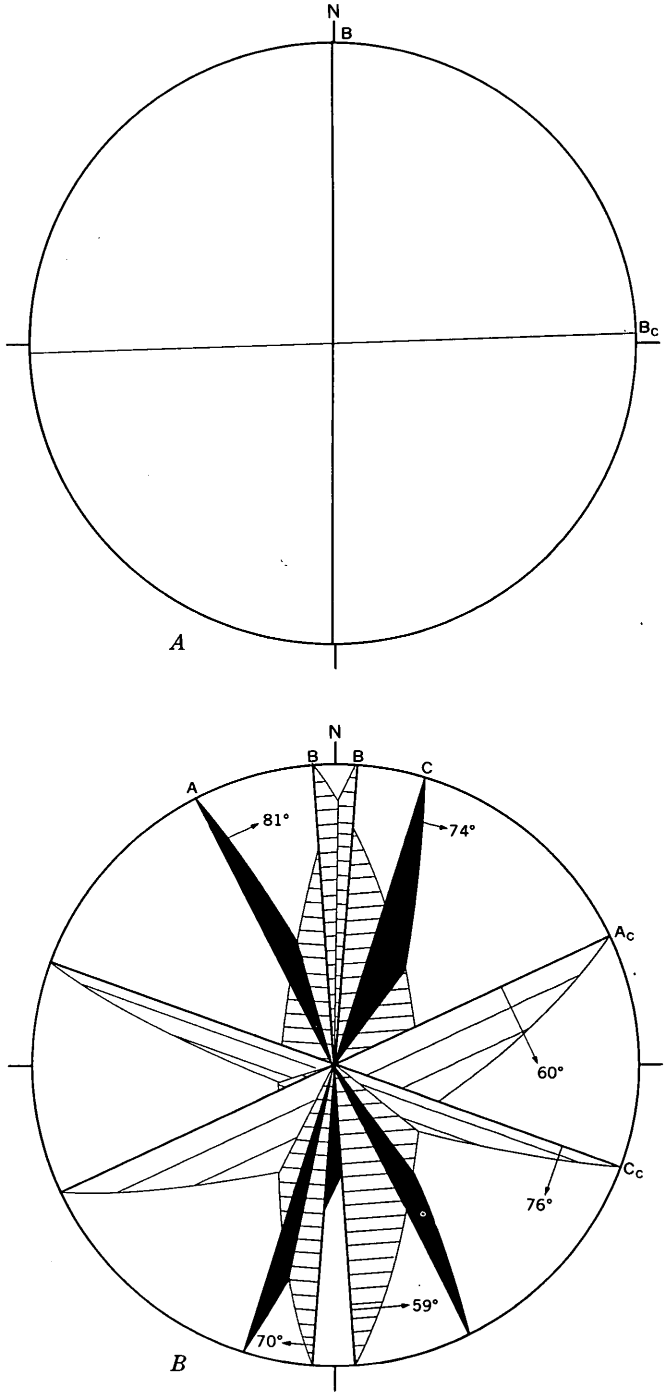


FIGURE 13.—Stereodiagrams showing principal joint sets in sedimentary rocks at Sandy mine. Plotted on lower hemisphere of Wulff net. Letters designate joint sets. *A*, Todilto limestone; maximums of 111 joint planes. *B*, Entrada Sandstone; maximums of 98 joint planes.

in the Dakota Sandstone around the open pit. The pattern in the Dakota is complete, containing all six joint sets recognized in the district; all are about vertical. In the Jackpile sandstone, all sets likewise occur but the B set apparently separated into two inclined B sets whose intersection plunges north at a low angle. The whole pattern in the Jackpile sandstone is rotated slightly counterclockwise from its orientation in the Dakota Sandstone.

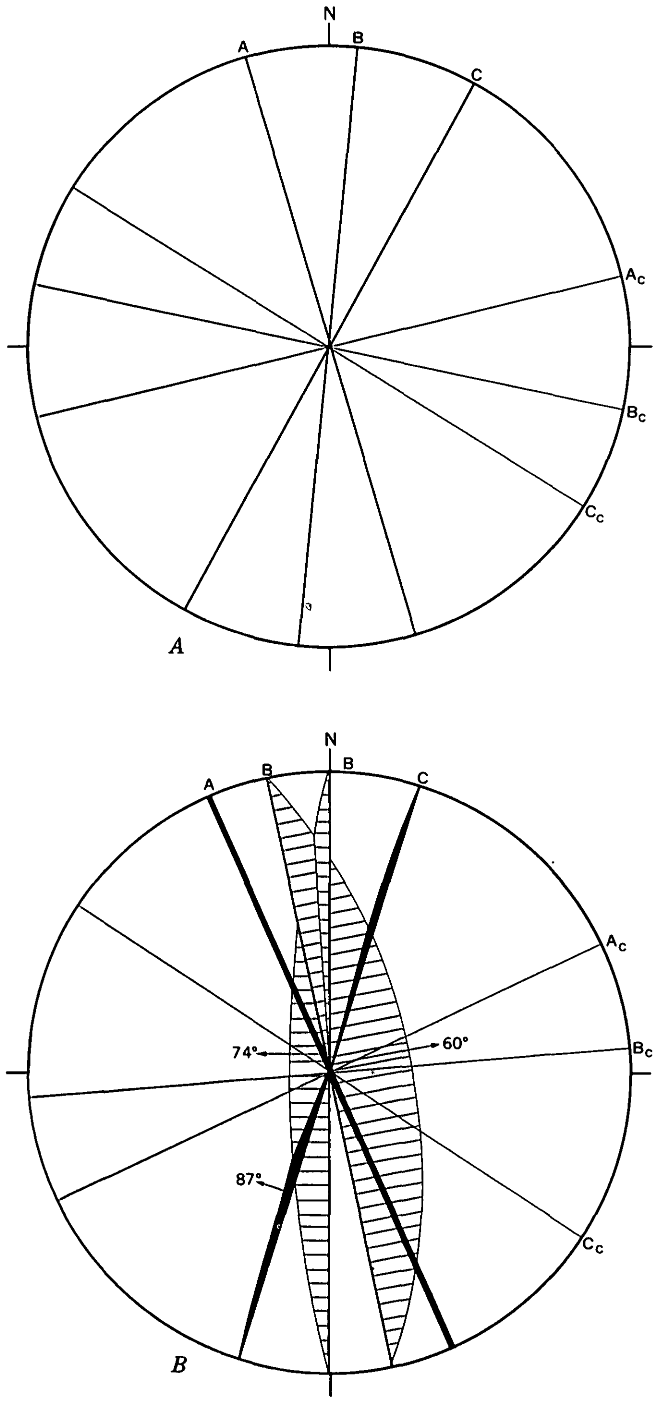


FIGURE 14.—Stereodiagrams showing principal joint sets in sedimentary rocks of Jackpile mine. Plotted on lower hemisphere of Wulff net. Letters designate joint sets. *A*, Dakota Sandstone; maximums of 67 joint planes. *B*, Jackpile sandstone of economic usage; maximums of 172 joint planes.

Within a small area a fracture pattern can be expressed differently in different stratigraphic units. The area of diagram 11, plate 4, for example, contains all elements of the major joint system; but if all measurements in this area are plotted in two diagrams—one for the Cretaceous rocks and one for the Jurassic rocks (fig. 15)—we find that the A, B, and C sets and the corresponding cross(?) joint sets are well developed in the Jurassic rocks, whereas the B set and its corresponding cross(?) set are missing in the Cretaceous rocks.

RELATIONS BETWEEN FRACTURES AND FOLDS

Except in part of the San Ignacio faulted monocline, no obvious relation exists between fractures and folds. Hodgson (1961, p. 26, 37) drew a similar conclusion about the joint patterns in the central part of the Colorado Plateau. Fold axes and structure contours are highly sinuous, whereas faults and joints are relatively persistent in trend (pl. 4). Further, the fractures generally transect even the general trends of the folds. Except in the area south of Laguna, faults seem to be more abundant where structure contours bend sharply as near the crestline and north end of the Madera anticline and in a northwest-trending zone just north of Piedra Lumbre. A genetic relationship between fractures and folds is not demonstrated however. The flexed areas, for example, may have been weakened, so that they were more easily faulted at a later time.

Joints do not exhibit a specific geometric relation to the folds west of the San Ignacio faulted monocline. The Arch Mesa basin, with a relief of more than 200 feet in less than 9 square miles, is one of the most pronounced structural features west of the fault zone. The joint pattern in and around the basin is identical with the district-wide pattern; it is not concentric or radial to the basin (fig. 16). Longitudinal, cross, or diagonal joints that might be related to the Arch Mesa syncline as a whole have not been recognized.

RELATIONS BETWEEN FRACTURES AND DIABASE

Some fracturing is younger than the diabase sills, and some is older. Most high-angle dikes parallel the north-trending B set of joints, which indicates that this joint set existed before the diabase was emplaced. On the other hand, all sets of the joint system can be recognized in diabase sills, in addition to primary joints that formed during emplacement and cooling of the diabase (Balk, 1948, p. 34–36).

In the area southeast of Laguna, several faults displace diabase sills. Although dikes are parallel to the

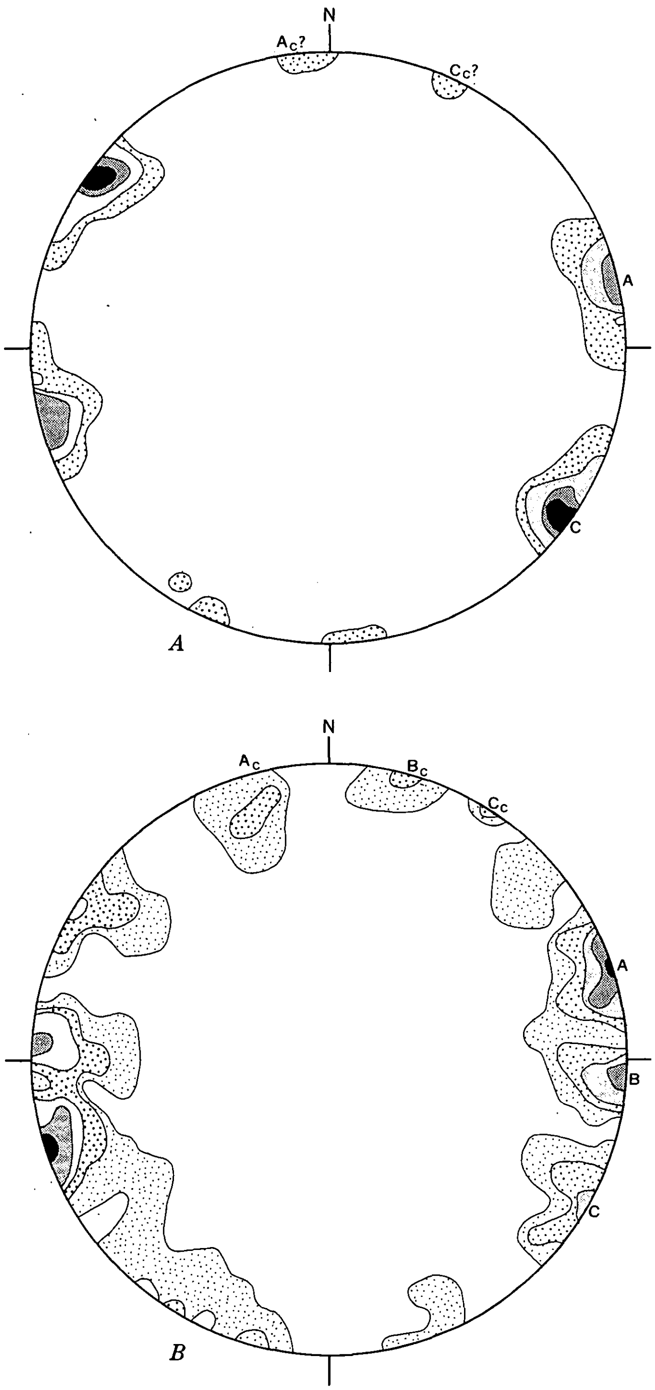


FIGURE 15.—Joint patterns in Cretaceous and Jurassic rocks of area 11, plate 4. Poles of joints plotted and contoured on upper hemisphere of Schmidt net. Letters designate joint sets. *A*, Cretaceous rocks; 42 poles. Contour interval 5 percent. *B*, Jurassic rocks, 102 poles. Contour interval, 2 percent.

north-trending faults and B joints, they do not appear to have been emplaced along faults. Nowhere does displacement along dikes appear to be more than that attributable to the thickness of the dike or an adjoining sill.

COMPARISONS WITH FRACTURE PATTERNS IN OTHER PARTS OF THE COLORADO PLATEAU

Various studies of fracture patterns on the Colorado Plateau (Duschatko, 1953; Gilkey, 1953; Hodgson, 1961; Kelley and Clinton, 1960) indicate that the major pattern in the Laguna district may extend over much of the extreme east side of the plateau but probably not far to the west. In the Lucero uplift, a few miles southeast of the Laguna district, the dominant fracture pattern consists of three sets that trend about N. 5° E., N. 12° W., and N. 25° E., (Duschatko, 1953), almost identical with the major joint system and accompanying faults and dikes in the Laguna district. Unlike the pattern in the Laguna district, however, the N. 5° E. set and the other two sets (A, B, and C sets, respectively, in our terminology) do not occur in the same areas (Duschatko, 1953). In the Zuni uplift, to the west, the most continuous fractures trend northwest, about parallel to the axis of the uplift (Gilkey, 1953). The pattern in the Comb Ridge–Navajo Mountain area of the central part of the plateau appears to be dominated by east-west, northeast, and southeast trends (Hodgson, 1961, pl. 1), unlike that in the Laguna district; locally there is a north-south trend.

ORIGIN OF FRACTURES

The north-trending faults and the north-northwest- to northeast-trending A, B, and C joints are interpreted to have formed about contemporaneously as a result of regional east-west elongation. This interpretation is consistent with theoretical and experimental studies of fractures and with the tectonics of the Rio Grande depression. The fact that the fracture pattern in the Laguna district extends without much change across the Lucero uplift to the south (Duschatko, 1953), but probably not far to the west, combined with evidence that the pattern formed in late Cenozoic time, suggests that fractures in the Laguna district resulted largely from tectonic activity in the Rio Grande depression.

Cloos (1955, pl. 1, figs. 1, 3) produced fracture patterns in clay that closely resembled the most conspicuous joint-and-fault pattern in the Laguna district. By nonrotational tensional deformation of the clay, the surface of which was liberally sprinkled with water, ten-

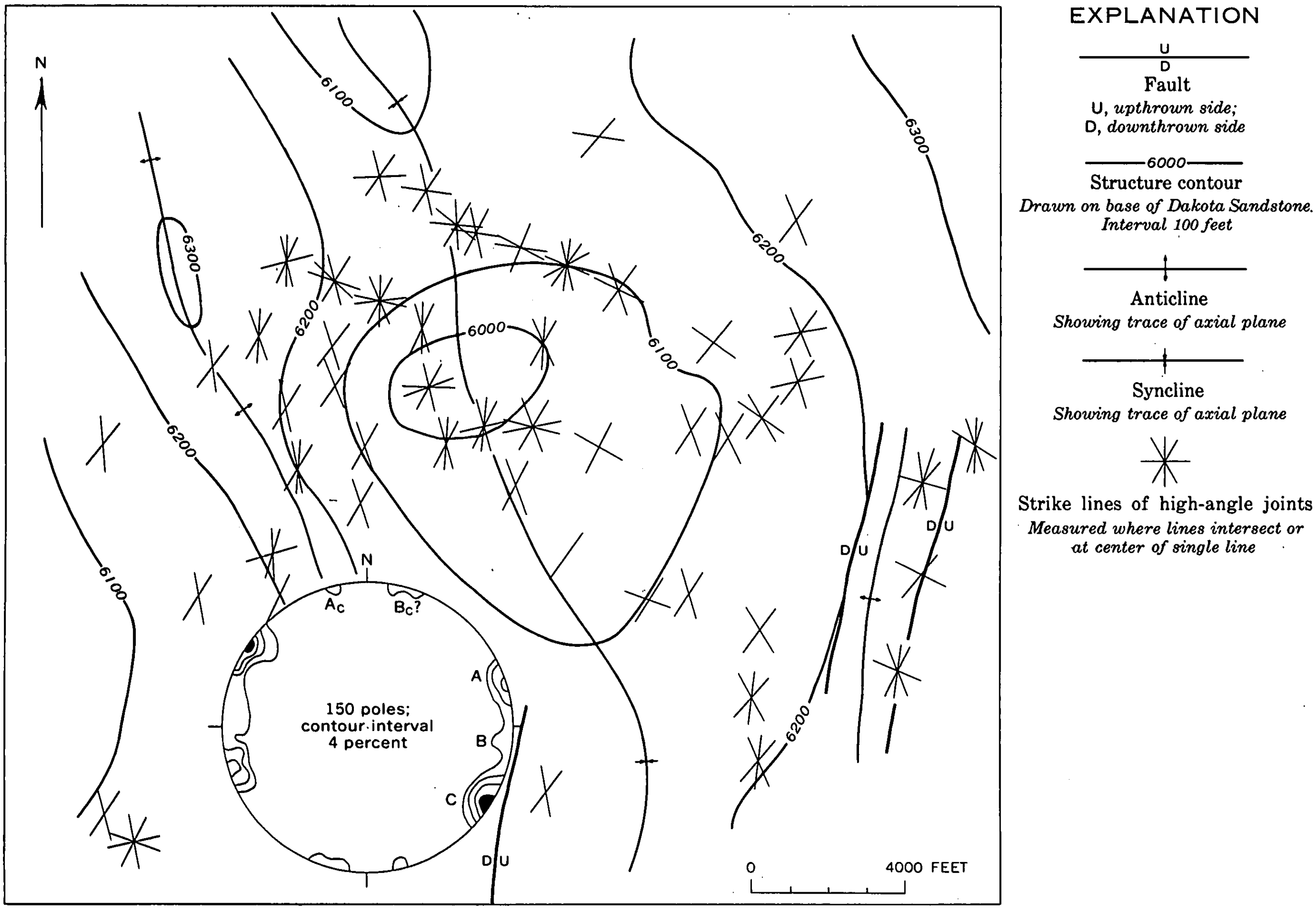


FIGURE 16.—Map showing orientation of joints in Arch Mesa basin.

sion fractures formed at right angles to the direction of tension. When the surface of the clay was kept dry, two sets of shear fractures appeared; the obtuse angle formed by the intersecting fractures was greater than 120°, and it was bisected along the direction of tension.

Similar patterns are likewise predictable by theoretical reasoning. Anderson (1942, p. 10, 11) related three major types of faults—thrust, wrench (strike slip), and normal—to three different orientations of maximum, minimum, and intermediate stress. From a mathematical analysis of fracturing he concluded that the direction of greatest pressure bisects the acute angle between intersecting fault planes in any rock. If only one of these planes is well developed, the direction of greatest pressure will be oriented at some angle less than 45° to the plane. DeSitter (1956, p. 131) suggested that Anderson's analysis can be applied to joints, including tension joints. According to DeSitter and other authors, tension joints occupy the plane of the maximum and intermediate stress directions and are normal to the minimum stress directions. In addition, so-called release-tension joints may form at right angles to the maximum stress direction after this stress is released. Such joints form, however, because the stress directions have changed; that is, maximum compression has changed to minimum compression, or to tension. If, as supposed in the Laguna district, the active tectonic stress was tensional and the maximum compression acted only in response to this tension, then release-tension joints are not likely to form.

In a simple stress system, therefore, three dominant sets of fractures may form: two shear joints (or faults) that intersect to form an acute angle bisected by the direction of maximum stress, and a tension joint that is parallel to the direction of maximum stress and bisects the acute angle between the two shear joints (or faults). The acute angle between the planes of shear failure may range from 0° to about 60°, depending upon the stress differences (Muehlberger, 1958). If so, a tension joint in the usual terminology may in some places represent a single plane of shear failure. Further, Hubbert (1951) pointed out that there is a certain critical depth below which tensional stresses cannot occur in a material of given strength; that is, tensional stress at or near the earth's surface becomes zero at the critical depth, and below this depth it is the minimum compressional stress in the stress system. Thus, true tension joints may be relatively uncommon.

In figure 17 the various expressions of the fracture patterns in the district are related to local stresses that developed in response to regional east-west tectonic elongation. The joints labeled *A*, *B*, and *C* strike N. 20° W., due north, and N. 20° E., respectively, and correspond to the similarly labeled joints on plate 4. For simplicity, the A_c, B_c, and C_c joints are not shown; they are thought to be unsystematic cross joints (Hodgson, 1961).

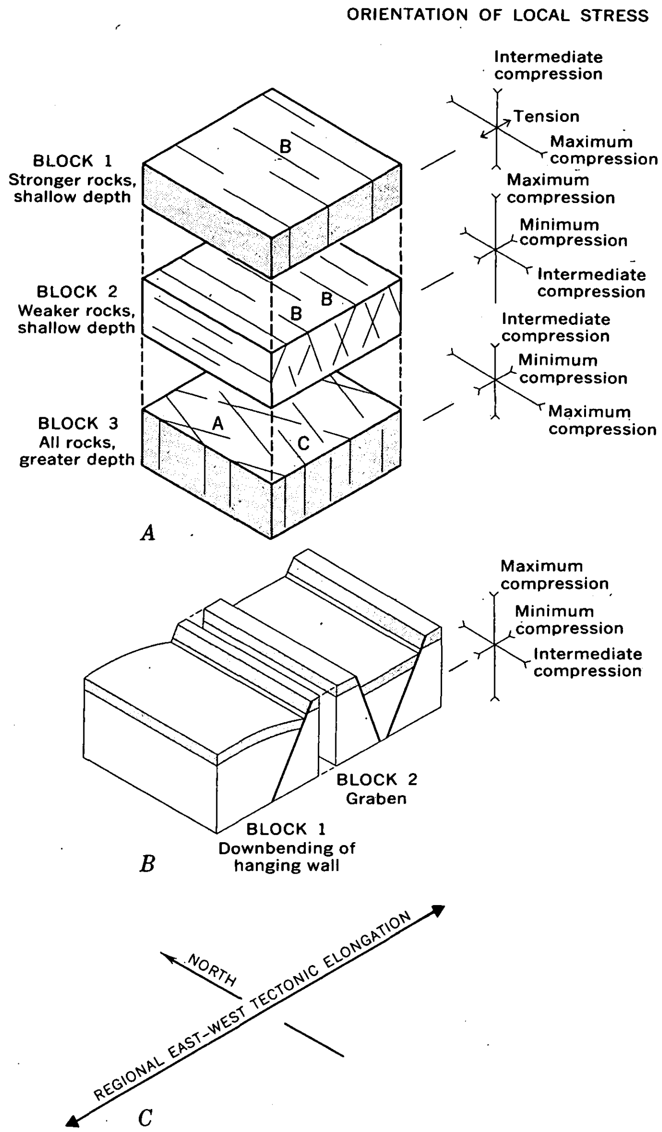


FIGURE 17—Idealized diagrams showing interpreted relations of joints and faults to local stresses and regional east-west elongation. *A*, Joint patterns in rocks of varying strength and depth. Letters designate joint sets. *B*, North-trending faults. *C*, Regional interpretation of stress field.

The fracture patterns illustrated in figure 17 may have formed in successive stages as overburden was eroded and confining pressure diminished. At maximum depth the confining pressure may have exceeded the maximum permissible confining pressure for tensional rupture in the strongest rocks (Hubbert, 1951). At high confining pressure the direction of maximum compression might be either vertical or horizontal and produce the respective joint sets shown in blocks 2 or 3 of figure 17*A*; which set formed would depend upon whether east-west elongation was compensated by vertical or by north-south shortening. Evidently, north-south shortening was dominant at a maximum depth, because A and C joints are present in both weaker and stronger strata and inclined B joints are absent from the relatively strong strata (figs. 13, 14).

At maximum depth, A and C joints (block 3, fig. 17*A*) probably formed by horizontal shear throughout; as overburden was removed, the role of gravity probably increased and inclined B joints (block 2, fig. 17*A*) formed by shear in the relatively weak strata.

As more overburden was eroded, confining pressure decreased further, and rupture under tension probably became possible in the strongest strata. At this stage, inclined B joints may have continued to form by shear in the weaker rocks, whereas vertical B joints formed by tension in the stronger rocks (block 1, fig. 17*A*). As still more overburden was eroded, rupture under tension became possible in progressively weaker rocks, and vertical B joints might have formed more widely. However, as all the rocks were previously jointed at greater depth, the formation of tension joints in new directions would be inhibited.

Normal faults (fig. 17*B*) might have formed at any stage during the removal of overburden. They strike normal to the direction of elongation but probably formed by shear under gravity. East-west elongation may be compensated by downbending of the hanging wall (block 1) or by the formation of a graben (block 2).

CENOZOIC TECTONIC HISTORY

In the vicinity of the Rio Grande depression, latest Cretaceous and early Tertiary time was marked by locally intense folding and thrust faulting due to east-west compression. Evidence of this deformation can be seen in the Caballo (Kelley and Silver, 1952), Los Pinos (Wilpolt and others, 1946), and Fra Cristobal (Jacobs, 1957) Ranges, all of which border the southern part of the Rio Grande depression, and in the Nacimiento Mountains (Wood and Northrop, 1946, and Dane, 1948), about 50 miles northeast of the Laguna district. In an oral communication to Kelley (1955, p. 85), Richard Koogle reported that on the north end of the Nacimiento uplift, vertical to overturned strata of Paleocene and older age are unconformably overlain by beds of Eocene age, which he called Wasatch (Simpson (1948) proposed that the name Wasatch be changed to San Jose) that are tilted westward toward the San Juan Basin as much as 40°. If these stratigraphic correlations and structural relations are correct, they provide perhaps the best dating of early Tertiary deformation in the region. They show that downwarping of the eastern part of the San Juan Basin took place in early Tertiary time, in part before and in part after San Jose deposition.

In the Laguna district the early Tertiary or Laramide deformation is expressed by the north-trending folds on the east side of the district and by the westward to northward dip toward the San Juan Basin. These features cannot be dated from evidence within the district, except that they deform the uppermost Cretaceous strata and are truncated by the high basalt-capped pediment of Pliocene or Pleistocene age. Tilting and folding along the San Ignacio faulted monocline might have started in early Tertiary time in response to east-west compression; but it more likely occurred in response to east-west tension in later Tertiary time. The faulted monocline is probably related at depth to a fault which might have been active during the period of intense faulting in the Rio Grande depression.

Although some subsidence took place in the Rio Grande depression in early to middle Tertiary time, as indicated by the stratigraphic record (Denny, 1940; Kelley and Silver, 1952; Stearns, 1953; Wilpolt and others, 1946), most subsidence took place in late Tertiary time, when the Santa Fe Group was deposited. According to Bryan (1938, p. 205), these alluvial and playa-basin deposits form the main body of sediments in the depression from the north end of the San Luis Valley, Colo., southward at least to El Paso, Tex. On the basis of vertebrate fauna, the Santa Fe Group is thought to be largely Pliocene in age, but it may in part be as old as late Miocene (Bryan and McCann, 1937; Bryan, 1938; Denny, 1940) and as young as early Pleistocene. That such a thick sequence of sediments is confined to such a long narrow belt is in itself strong evidence of depression contemporaneous with sedimentation. As shown by Bryan and McCann (1937), Hunt (1938, p. 77), and Wright (1946), these events were preceded, accompanied, and followed by much high-angle faulting in the depression. They were evidently followed in Pliocene or early Pleistocene time by a stage of tectonic stability, when the so-called Ortiz erosion surface was formed (Bryan and McCann, 1938), and then by uplift and deep erosion.

Late Cenozoic deformation in the Laguna district was primarily jointing and faulting, which evidently accompanied late Tertiary tectonic activity in the Rio Grande depression. This relation is supported by the apparent restriction of the major fracture pattern to the east side of the Colorado Plateau, and by the absence of a detectable relation between fractures and folds except in the San Ignacio faulted monocline. Undoubtedly, however, the large Rio Grande depression influenced the bordering areas in some way. If we assume that the depression reflects east-west elongation under crustal tension (DeSitter, 1956, p. 143, 235), the fracture pattern in the Laguna district can be interpreted most easily in terms of the tectonics of the depression.

The fact that at least one north-trending fault cuts a basalt flow that caps the Ortiz erosion surface suggests that east-west elongation continued after major tectonism in the Rio Grande depression ended.

GEOMORPHOLOGY

The Laguna district, which is characterized by mesa topography typical of the Colorado Plateau, reflects successive geologically recent periods of valley deepening interspersed with periods of valley widening. The region has been carved to depths of as much as 1,500 feet below an extensive erosion surface, and large volumes of material have been carried away.

Two contrasting types of mesas are present in the district: mesas whose tops are basalt-capped relict pediments, and mesas whose tops are formed by resistant sedimentary strata that have been stripped of less resistant overlying beds. The surface beneath the basalt slopes southward and truncates successively older Mesozoic strata. Mesa Chivato, a broad area as much as 8,000 feet in altitude, is a basalt-capped mesa that extends into the northwest corner of the district (fig. 1, GQ–207). Mount Taylor is at the south end of the mesa; sheet basalts cover the rest of the mesa and in places underlie the volcanic rocks of Mount Taylor. Where the mesa extends into the district, its top is formed by at least two basalt-capped pediments called the Mesa Chivato surface and the lower Wheat Mountain surface. The Wheat Mountain surface is about 200–300 feet lower than the Mesa Chivato surface and underlies the small volcanic cone and associated flows that cap Frog and Clay Mesas (fig. 1, GQ–208). Mesa Gigante (fig. 1, GQ–212) is a stripped-surface mesa, as are most of the mesas and benches that are lower than Mesa Chivato. Such mesas or benches are capped by resistant sedimentary rocks: the limestone of the Todilto Formation, the Bluff or Dakota Sandstones, or any of the seven higher sandstone strata of Cretaceous age. The overlying shales and mudstones have been eroded, and the graded surfaces or pediments that probably extended over them have been destroyed.

Several relict pediments are present at lower levels around the base of Mesa Chivato, and one or two are present near the Arroyo Colorado. Those around the base of Mesa Chivato range from 40 to more than 200 feet above the lowest nearby drainage level and slope away from the high mesa at a grade of about 100 feet to the mile. Those south of Mesa Chivato are covered with coarse gravel composed of basalt and porphyritic igneous rock derived from Mount Taylor, whereas those to the east are covered with coarse gravel composed of basalt derived from Mesa Chivato. Tsidu-Weza (Moench, 1964a) rises about 200 feet above the surrounding terrain; it is part of the Mush Mesa surface of Wright (1946, p. 449), several remnants of which are present south of the district. Tsidu-Weza is capped by basalt derived in part from a neck on the west end of the mesa. In the southeast corner of the district, a basalt-capped relict pediment is present about 100 feet above the Arroyo Colorado valley floor (Moench, 1964a); it forms part of the so-called Suwanee surface of Wright (1946, p. 449).

ORTIZ SURFACE

Bryan and McCann (1938, p. 11) and, later, Wright (1946, p. 435–444) correlated the top of Mesa Chivato with the so-called Ortiz surface that once extended over a large part of New Mexico in the vicinity of the Rio Grande. This surface was graded to the ancestral Rio Grande, at a level about 500 feet above the present level of the river. It truncates sediments of the Santa Fe Group, which are largely of Pliocene age, and in many places is underlain by thick caliche deposits. From these relations Bryan and McCann (1938) inferred that the surface marks a period of tectonic stability in the Pleistocene. Because of uncertainties in the correlation, the highest erosion surface under the basalts on Mesa Chivato is called, in this report, the Mesa Chivato surface.

The Mesa Chivato surface slopes southward at a grade of about 80 feet per mile. The surface is irregular, apparently owing largely to the intersection of resistant sandstone beds with the surface. If extended southward across the Rio San Jose, it would intersect Casa Blanca Mesa about 200 feet below its top, and other higher mesas to the south at still lower levels. These relations indicate that the Mesa Chivato surface probably was graded to the ancestral Rio San Jose at a level about 650–700 feet above the present river. This surface also could have extended over Mesa Gigante and over all other mesas with stripped surfaces in the district. If we assume that the ancestral Rio San Jose was about 700 feet directly above its present position about 5 miles south of Mesa Gigante, a pediment rising northward at 80 feet per mile from the river would extend over the south end of the mesa.

The Mesa Chivato surface, though extensive, was never completely pedimented. Cretaceous sedimentary rocks are exposed in the Mount Taylor amphitheater at an altitude of about 9,100 feet—more than 1,200 feet above the highest part of the Mesa Chivato surface in the Laguna district 3½ miles farther east. This means that Cretaceous strata were exposed in hills, buttes, or mesas that rose at least a thousand feet above the Mesa Chivato surface.

The Wheat Mountain surface slopes southward and was probably graded to the Rio San Jose at a level about 400–500 feet above the present river in the area west of Laguna. This surface was not as extensive as the Mesa Chivato surface and could not have extended over Casa Blanca Mesa, south of the river.

GEOMORPHIC HISTORY

After block faulting and accumulation and deformation of the Santa Fe strata, the Ortiz surface was cut across the deformed strata, and was extended far beyond the limits of the Rio Grande depression. Subsequently, the base level of the major controlling drainage, the Rio Grande, was rapidly lowered in several successive stages. Each drop in base level initiated a stage of canyon cutting and of broadening of the resulting canyons by pedimentation. Each stage left a terrace that was partly or completely destroyed by the following stage. Relict pediments survived in places, particularly where they were protected by a basalt cap. Some mesas formed as less resistant materials were stripped to expose resistant strata. At present the region is probably in a downcutting stage, because most of the drainage is entrenched. It is not known whether the most recent entrenchments reflect uplift, climate change, or other factors.

If Bryan and McCann (1938) and Wright (1946) were correct in correlating the top of Mesa Chivato with the Ortiz surface, the fact that the Ortiz surface is late Pliocene or Pleistocene in age indicates that erosion has been rapid since that time. Not only is this surface incised to a depth of as much as 1,500 feet, but broad valleys have been formed. A great volume of material has been removed.

URANIUM DEPOSITS

The discovery of the Haystack Butte deposit west of Grants, N. Mex., in 1950 by Paddy Martinez, a Navajo Indian prospector, stimulated intensive prospecting along the south margin of the San Juan Basin (Melancon, 1963). Two large uranium districts—the Ambrosia Lake district, north of Grants, and the Laguna district (pl. 5)—were developed; reserves total more than 50 million tons of uranium ore. Several multimillion-ton deposits were found in sandstone of the Morrison Formation in both districts. The Jackpile deposit, in the Laguna district, was the first and largest deposit found on the southern margin of the San Juan Basin; it contained many millions of tons of ore. Many deposits were found in the limestone of the Todilto Formation, the largest containing about half a million tons of ore. A few small deposits, each containing less than 3,000 tons of ore, were found in the Entrada Sandstone.

The discovery of the Jackpile deposit in 1951 by the Anaconda Co. established the Laguna area as a mining district. For several years, production from a single mine (the Jackpile mine) in this district exceeded the combined production from all other uranium mines in the United States. The Saint Anthony Uranium Corp. discovered the relatively small M–6 ore body in 1955 and began development late in 1956. Stripping operations on Anaconda's Paguate deposit, which compares with the Jackpile deposit in areal extent, were begun in 1961.

The uranium deposits of the Laguna district are in two main stratigraphic sequences: (1) sandstone strata of the Morrison Formation, and (2) the limestone of the Todilto Formation and uppermost unit of the Entrada Sandstone. These two sequences are separated by the barren Summerville and Bluff Formations—an interval of about 400 feet. Except a few small deposits in the Dakota Sandstone near Grants and Gallup (pl. 5), no uranium deposits have been found in the Cretaceous or pre-Jurassic rocks in the southern San Juan mineral belt. Most deposits in the clastic sediments are semitabular and are similar in many respects to most deposits elsewhere on the Colorado Plateau. Although deposits in the limestone are more stringlike or rodlike in form, they are closely associated with the semitabular deposits in the Entrada Sandstone. Two pipelike deposits in the Jackpile sandstone have been mined in the district, but many more probably exist.

The uranium deposits of the Laguna district differ from one another by details of their composition, form, and stratigraphic and structural relations, but their similarities suggest that they belong to the same class and had a common origin. Their salient characteristics suggest an origin early in the postdepositional history of the host rocks.

SOUTHERN SAN JUAN BASIN MINERAL BELT

The deposits in the Laguna district form the east end of the southern San Juan Basin mineral belt (Hilpert and Moench, 1960). This belt of uranium deposits is at least 85 miles long and 20 miles wide and trends east-southeast from Gallup to the Laguna district (pl. 5), where it apparently swings east-northeastward. Although its origin is not known, the belt parallels several controlling and definitive geologic features. Hilpert and Moench (1960, p. 462) stated:

> In addition to the Jurassic highland and the southern limits of the Todilto limestone and the Morrison formation, it parallels the easterly trend of the major Jurassic folds, the dominant orientation of the intraformational folds in the Todilto limestone, the elongation of the thickest parts of the host sandstones of the Morrison formation, the dominant known sedimentary trends within these host sandstones, and finally, it parallels the individual belts of deposits * * *.

This statement applies to the whole mineral belt and summarizes the chief relationships in the Laguna district. The areal distribution of deposits in the district is shown on plate 3.

The south margin of the mineral belt is gradational but well defined in the Laguna district. The south side of the Jackpile sandstone, the major host rock in the district, is unconformably truncated. Farther south only a few small deposits are present in stratigraphically lower sandstone beds of the Morrison Formation, in the limestone of the Todilto Formation and in the Entrada Sandstone. No deposits are known either in the pre-Jurassic rocks in the southern part of the district or in the Jurassic rocks of the so-called Jurassic overlap (Silver, 1948) south of the district.

The north margin of the belt is less well defined, because in much of this part of the area the favorable host rocks are at too great a depth for detailed drilling or for mining under present economic conditions. Widespread drilling by the Anaconda Co. indicated that the Jackpile sandstone extends only a few miles northwest of the Jackpile mine. Uranium deposits may be present, however, to the northwest in stratigraphically lower rocks. A few small deposits have been found in the Jackpile sandstone in the northeast corner of the district (pl. 3), but to our knowledge none have been found in the area farther north, which has been prospected to some extent.

The mineral belt coincides with sedimentary and structural features of Jurassic age. In the Laguna district these features trend east or northeast (pl. 3), in contrast with the east-southeast trend of the mineral belt and its controlling features in the Ambrosia Lake district (Hilpert and Moench, 1960). The largest deposits in the Laguna district form the east-northeastward-trending Paguate–Saint Anthony group of deposits, which is in the central and thickest part of the Jackpile sandstone (pl. 3). The northeastward trend of the Jackpile sandstone body is largely controlled by a large Jurassic syncline; sedimentary structural features within the unit parallel the long dimension of the syncline. The many small deposits at the Sandy mine and the several small deposits a short distance to the south similarly form two east- to northeast-trending groups that are controlled by Jurassic folds.

There is, however, little relation between the mineral belt and Cenozoic igneous rocks or structural features. The belt is nearly normal to the trends of the Lucero and Nacimiento uplifts, the San Ignacio faulted monocline, the Rio Grande depression, and the McCartys syncline (pl. 5). The mineral belt is also nearly normal to the belt of volcanic centers that extends northeast from near Mount Taylor. Most faults between Gallup and the Rio Grande depression trend north or northeast, and the dominant joint system in the Laguna district consists of three sets of joints that trend north-northwest to northeast. However, the Zuni uplift, south of the mineral belt, is elongate about parallel to the mineral belt. This uplift conforms approximately to the lines of pinchout of the Todilto and Morrison Formations and was a structurally positive area during much of its pre-Cretaceous history. The mineral belt also follows the south margin of the San Juan Basin, which probably attained its present configuration in early Tertiary time.

CONTRASTING HOST-ROCK CHARACTERISTICS

The upper unit of the Entrada Sandstone, the Todilto limestone, and sandstones of the Morrison Formation have few characteristics in common, and they represent widely contrasting environments of deposition. The upper unit of the Entrada Sandstone is a widespread tabular unit of clean well-sorted sandstone and, in part, represents eolian deposition; the Todilto limestone is largely an extensive chemical precipitate; the sandstones of the Morrison Formation, especially the Jackpile, are lenticular arkosic fluvial deposits. Fragmental plant remains are abundant in the Morrison Formation but absent from the Entrada; the Todilto contains unidentified organic material (it has a fetid odor when broken). Relict volcanic ash may account for much of the mudstone of the Morrison Formation; but except for sparse books of biotite (Weeks and Truesdell, 1958), little if any volcanic material is present in the Entrada and Todilto Formations. The upper part of both the Jackpile and the Entrada is composed of nearly white altered rock; though the type of alteration products differs, both alterations probably took place shortly after the deposition of the respective rocks.

The three host rocks differ greatly with respect to transmissivity, which Jobin (1962, p. 6) defined as the product of the mean permeability and total thickness of the transmitting medium. In this report, "transmissivity" is used only qualitatively. The limestone of the Todilto Formation is probably nearly impermeable, except along fractures. As most fractures in this unit formed in late Tertiary and Quaternary time, the prior transmissivity of the limestone was probably low, although intraformational folds and associated penecontemporaneous fractures may have provided local channels of relatively greater permeability. The Entrada Sandstone, in contrast, is a widespread thick sheetlike permeable sandstone deposit and is one of the most transmissive units in the region. Superficially, the Jackpile sandstone seems to be a highly transmissive unit: it is friable, locally very thick, and, on the basis of the amount of water that has to be pumped from the Saint Anthony mine, fairly permeable; it is, however, of limited areal extent (pl. 3). It is overlain by the Dakota Sandstone and underlain by the relatively impermeable mudstone of the Brushy Basin Member of the Morrison. Prior to recent erosion, the Jackpile sandstone may have been a lens of sandstone that was fairly well sealed on all sides, except possibly on its northeast end. The overlying Dakota Sandstone is not a good aquifer in the region (Dinwiddie, 1963, p. 217) and probably has only a small degree of lateral transmissivity; the abundance of black shale at or near its base would inhibit the exchange of water between the Dakota and the Jackpile. After truncation and burial beneath the Dakota, the Jackpile sandstone probably had very low regional transmissivity, compared to the Entrada or Bluff Sandstones.

Though detailed comparisons between the host rocks and all the barren stratigraphic units in the region would be voluminous, a few characteristics should be mentioned. Like the sandstones of the Morrison Formation, the sandstones of Cretaceous age contain abundant plant remains which are largely coalified; plant remains in the Jackpile sandstone, however, are mostly silicified, and are coalified only locally. The sandstones of the Recapture, Westwater Canyon, and Brushy Basin Members of the Morrison contain so-called "trash pockets" of coalified plant debris and associated uranium deposits, but they contain silicified plant remains also. The Cretaceous sandstones are light tan or nearly white, like the Jackpile sandstone, but they are largely mineral cemented and are not much altered. Continental deposits of Triassic age such as the Correo Sandstone Member of the Chinle contain abundant silicified logs, but this unit is various shades of red and shows only local effects of alteration. The Bluff Sandstone and

Summerville Formation show effects of alteration, but they are notably devoid of organic remains.

COMPOSITION OF THE ORES

In addition to the minerals of the host rocks, the uranium deposits of the district contain uranium, vanadium, and sulfide minerals plus variable amounts of carbonaceous matter. In the unoxidized deposits the uranium minerals are uraninite and coffinite. In deposits in the Morrison Formation these minerals are intimately mixed with black carbonaceous matter, which fills grain interstices and markedly darkens the sandstone. In deposits in the Entrada Sandstone and Todilto Formation, carbonaceous matter is sparse; uraninite and coffinite fill interstices of the sandstone and are distributed along laminae and grain boundaries of the limestone. Uraninite and coffinite are typically extremely finely divided and are generally identifiable only by X-ray. Coffinite that is sufficiently coarse to be identified optically has been found only in a vug in the Woodrow deposit (Moench, 1962b) and in mineralized logs in the Jackpile deposit. Vanadium is contained largely in mixed-layer mica-montmorillonite and chlorite, which are collectively termed "vanadium clay." This material is generally vermicular and fills pore spaces in the vanadium-rich ores. Pyrite, the dominant sulfide mineral, is disseminated through all unoxidized deposits. The Woodrow deposit contains abundant marcasite and trace amounts of galena, wurtzite, cobaltite, and chalcopyrite. Barite has been found in most deposits studied. Where oxidized, the deposits contain a great variety of high-valent uranium and vanadium minerals that unquestionably formed by oxidation of low-valent uranium and vanadium minerals in fairly recent times. As they have little bearing on the origin and localization of the deposits, the high-valent uranium and vanadium minerals are discussed only briefly in this report.

A few ore specimens contain as much as 20 percent uranium, but not many contain more than 1 percent uranium or vanadium; most ores average about 0.2 percent uranium and still less vanadium. Ore containing as little as 0.04 percent uranium has been shipped from the Jackpile mine. Unlike most other kinds of ore deposits, then, typical uranium ore does not differ greatly in bulk composition from the host sandstone.

The terms "ore" and "barren rock" are used in a loose sense in this report. "Ore" is conveniently used synonymously with "uranium deposit" and means rock that, with exceptions, contains in excess of 0.1 percent uranium. Since uranium is probably detectable in very small quantities in all rocks of the area, no rock is strictly barren of uranium. "Barren rock" is all rock that is not obviously mineralized.

HOST-ROCK MINERALOGY

The most obvious mineralogic difference between the main host rocks is the amount of calcite present. The Jackpile sandstone is largely clay-cemented quartz sandstone in its upper part and quartz- and calcite-cemented subarkose in its lower part. Calcite is largely confined to the lowermost part of the unit, and there it forms sparse "sand crystals." Where studied, the Jackpile and Windwhip deposits are above the carbonate zone. Of 10 samples from the Jackpile mine that were analyzed for total, organic, and mineral carbon, only 2 had detectable amounts of mineral carbon—0.69 percent (5.7 weight percent $CaCO_3$) and 0.06 percent (0.5 weight percent $CaCO_3$), respectively. Quartz overgrowths and kaolinite are present in both ore and host rock.

The Entrada Sandstone is, in contrast, largely calcite-cemented. Mineral-carbon determinations of rock from below and above the Pit I deposit in the Sandy mine showed 2.81 percent (23.4 weight percent $CaCO_3$) and 2.99 percent (25.0 weight percent $CaCO_3$), respectively; these determinations compare, respectively, with 27 and 28 volume percent calcite, determined by modal analysis (table 5). Clay is not as abundant in this rock as in the Jackpile sandstone, and most clay is mixed-layer mica-montmorillonite and some chlorite; no kaolinite was found (J. C. Hathaway, analyst).

Todilto limestone is largely carbonate rock that has fine-grained detrital quartz, feldspar, and clay minerals distributed along bedding planes.

Typical mineralized and unmineralized specimens of Jackpile sandstone are similar with respect to clay mineralogy; differences appear to be related to variations in sand content and to be unrelated to ore. Table 4 summarizes these relationships. In samples 1–4, each of which contains more than 80 percent sand and less than 10 percent silt and clay, kaolinite is the dominant clay mineral. In samples 5 and 6, which are finer grained than samples 1–4 and contain about 75 percent sand and more than 10 percent each of silt and clay, mixed-layered mica-montmorillonite is the dominant clay mineral. Chlorite is in only two of the mineralized samples listed in table 4. Coffinite, probably mixed with carbonaceous matter, is abundant in one sample. Viewed in thin sections, kaolinite forms aggregates of booklets that fill the interstices between four or five sand grains. The booklets are randomly oriented and range from almost submicroscopic to silt size. What is probably mixed-layered mica-montmorillonite generally occurs as flakes wrapped around sand grains and appears to be more homogeneously distributed but less abundant than the kaolinite.

TABLE 4.—*Mechanical analysis and mineralogy of six samples from the Jackpile mine*

[Sample: U, unmineralized; W, weakly mineralized; M, mineralized. Tr., trace. Analysts: J. C. Hathaway, H. C. Starkey, and G. W. Chloe]

Sample	1 U	2 W	3 M	4 M	5 U	6 M
Distribution, in percent, by particle size, in microns						
Sand (>62)	81.5	89.3	84.4	88.1	75.6	75.1
Silt (2–62)	8.0	4.4	8.4	6.2	13.0	11.7
Clay (<2)	9.0	10.1	5.3	5.4	10.5	12.8
Total	98.5	103.8	98.1	99.7	99.1	99.6
Clay-fraction mineralogy, estimated amounts in parts per 10						
Kaolinite	3	5	5	3	0	2
Montmorillonite (with some mica)	2	2	0	2	0	0
Mixed-layer mica-montmorillonite	0	0	2	0	6	3
Chlorite	0	0	Tr.	0	0	2
Quartz	4	2	1	1	3	2
Coffinite	0	0	0	3	0	0

Modes of specimens of the Entrada Sandstone taken across the Pit I deposit of the Sandy mine are shown in table 5. The analyses were made by the point-count method, about 500 points per thin section. The barren sandstone above (OS–1g) and below (OS–1a, 1b) the deposit has a remarkably uniform composition. Unmineralized sandstone between the ore layers (Os–1d) is similar in composition but contains slightly less sand and silt, slightly more calcite, and no silica cement. Calcite in this rock (Os–1d) occurs in poikilitic crystals about half an inch in diameter that corrode the detrital grains, whereas calcite in rock above and below the deposit is in much smaller grains. Within the deposit the abundance of calcite decreases as the abundance of vanadium clay increases. In the upper ore layer, detrital sand and silt particles are less abundant than in unmineralized sandstone. The ordinary (Omega) refractive index of calcite in all specimens in table 6 is 1.659 (for sodium light at 25°C), which is about equal to that of pure calcite.

The clay-size fraction of unmineralized Entrada Sandstone contains about 60 percent mixed-layer mica-montmorillonite (about 1:1), 20 percent chlorite, and 10 percent each of montmorillonite and calcite (determined by mechanical and X-ray analyses by J. C. Hathaway). The clay-size fraction of ore has a similar mineralogic composition, except that the mixed-layer mica-montmorillonite contains proportionately more mica.

MINERALS OF UNOXIDIZED URANIUM DEPOSITS

X-ray analyses show that coffinite is generally the dominant low-valent uranium mineral in the ores of the Jackpile sandstone (including the Woodrow deposit), and that uraninite is also present. Both coffinite and uraninite are abundant in the Pit I deposit, in the Entrada Sandstone, at the Sandy mine, whereas uraninite is probably dominant in deposits in limestone of the Todilto Formation. The Crackpot deposit, in limestone, was already mined out when this project started in 1955, and adequate material for X-ray study was not available; however, Gabelman (1956, p. 339) reported the occurence of pitchblende in the Crackpot mine. Numerous X-ray determinations that have been made on ores from limestone in the Ambrosia Lake district (Laverty and Gross, 1956, p. 200; Alice F. Corey, oral commun., 1957) clearly indicate that uraninite is the dominant low-valent uranium mineral in that area, but coffinite has been reported (Weeks and Truesdell, 1958; Truesdell and Weeks, 1959).

Most specimens of uraniferous carbonaceous matter from the Jackpile mine give X-ray powder patterns for coffinite, but many specimens show faint uraninite lines as well, and in some specimens uraninite appears to be dominant; still others do not give identifiable patterns. The sharpest coffinite patterns were obtained from analysis of a coalified twig that shows woody structure, and of specimens of the carbonaceous matter that impregnates sandstone, surrounds mud galls, and lines the ring fault of the sandstone pipe. Some specimens from the ring fault and the sandstone impregnations, however, give only uraninite patterns. The coffinite

TABLE 5.—*Modes, in percent, of a sequence of specimens taken across the Pit I deposit, Sandy mine*

Sample (OS–)	Description	Sand and silt	Colorless clay	Calcite cement	Silica cement	Opaque cement	Vanadium clay
1g	Unmineralized sandstone, 1 ft above ore	63	7	28	1	[1] 1	0
1f	High-grade ore, top of ore layer above roll	49	0	19	1	[2] 1	30
1e	Low-grade ore, near bottom of ore layer above roll	50	0	21	0	[3] 2	27
1d	Unmineralized sandstone, between ore layers	62	6	32	0	0	0
1c1	Low-grade oxidized ore, center of ore layer below roll	66	17	9	5	[3] 3	0
1c2	Vanadium-clay-rich zone, in OS–1c1	65	0	0	0	[3] 3	32
1b	Unmineralized sandstone, 2 in. below ore	64	6	29	1	0	0
1a	Unmineralized sandstone, 1½ ft below ore	64	8	27	1	0	0

[1] Iron oxide.
[2] Uraninite and coffinite.
[3] Mostly iron oxide.

lines are characteristically sharp. whereas the uranite lines are diffuse; both may be present in a single film. In addition, the clay fraction of a sample of typical high-grade gray ore gave an X-ray powder pattern for coffinite (J. C. Hathaway, analyst). The sample contained 5.4 percent clay, of which about 3 parts in 10 were coffinite.

Although the Windwhip deposit shows more visible signs of oxidation than the Jackpile, it contains coffinite (Gruner and Smith, 1955), which probably accounts for most of the low-valent uranium in the deposit.

Coffinite, probably the dominant uranium mineral in the Woodrow deposit, is typically very fine grained and is associated with carbonaceous material that impregnates and replaces sandstone. It has been found in veinlets in a fossil bone fragment and in massive material that is also veined by pyrite and marcasite; it has also been found in a vug (Moench, 1962b). Uraninite from a drill core was identified by T. W. Stern (written commun., 1959).

X-ray patterns reveal both coffinite and uraninite in the Pit I deposit, Sandy mine, but one or the other predominates in different samples. Hard black lustrous material that adheres tightly to sand grains contains uraninite; black material that fills interstices contains abundant coffinite and a trace of uraninite; and handpicked material from the center of pyrite-rimmed concretions contain uraninite. The sand fraction (73 percent of the rock) of a sample of high-grade ore yielded less than 1 part in 10 coffinite; the silt fraction (18 percent of the rock) yielded about 2 parts in 10 coffinite; and the clay fraction (9 percent of the rock) yielded 3 parts in 10 coffinite (J. C. Hathaway, analyst).

The vanadium content of the unoxidized ores is at least partly attributable to vanadium clay, a fine-grained mixture of vanadium-bearing mica (probably roscoelite), montmorillonite, and chlorite. Other low-valent vanadium minerals, such as montroseite and haggite, may be present in small quantities.

Vanadium clay is abundant in the weakly oxidized and unoxidized ore in the Entrada Sandstone at the Sandy mine. As seen microscopically, the vanadium clay is vermicular, clove brown to greenish brown, slightly pleochroic, and moderately birefringent. Its approximate beta-gamma index of refraction is 1.63, and its specific gravity is about 2.8–2.9 (suspends in bromoform). A quantitative spectrographic analysis of one separate revealed 8.6 percent vanadium, and a semiquantitative analysis of the same separate revealed 7 percent aluminum, 7 percent potassium, 3 percent iron, 1.5 percent magnesium, 1.5 percent calcium, and 7 percent uranium, plus minor elements (Nancy M. Conklin, analyst). The calcium and uranium are probably contained in calcite and uraninite impurities. Fairly pure vanadium clay from the Sandy mine contains about 80 percent mica (probably roscoelite), with some interstratified montmorillonite layers, and about 20 percent chlorite (J. C. Hathaway, analyst, by X-ray diffraction).

Vanadium clay seems to be widely distributed, for optically similar material from several other deposits in the Sandy mine area and from the Crackpot, Chavez, and Jackpile deposits gives similar X-ray diffraction patterns. Strongly mineralized silicified logs in the Jackpile deposit contain veinlets of micaceous material that gives a roscoelite X-ray powder pattern. This material is darker brown than the vanadium clay in other deposits, but its other optical properties, X-ray pattern, and form are similar; semiquantitative spectrographic analysis revealed 7 percent vanadium, 7 percent aluminum, 3 percent iron, 7 percent potassium, 1.5 percent uranium, and other minor elements; spectrographic analysis of handpicked vanadium clay from the Crackpot mine revealed 7 percent vanadium, 3 percent aluminum, 3 percent iron, 1.5 percent magnesium, 1.5 percent calcium, 7 percent potassium, and other minor elements (Nancy M. Conklin, analyst).

Vanadium clays from other parts of the Colorado Plateau are similar to those described here and were studied in detail by Foster (1959) and by Hathaway (1959). These studies suggested that the vanadium in the vanadium clays in the Laguna district and other parts of the plateau is in both trivalent and tetravalent states. It is undoubtedly a part of the mica and clay molecular structure, not a superficial impregnation of clay by vanadium.

Sulfide minerals are present in all the unoxidized deposits, but the Woodrow deposit contains by far the most. Pyrite appears to be the most abundant sulfide mineral; marcasite is locally abundant, especially in the Woodrow deposit. Trace amounts of galena have been found in the Jackpile and Woodrow deposits and in the Pit I deposit at the Sandy mine. Chalcopyrite is commonly associated with coffinite in the Woodrow deposit, and a trace amount has been found in the Pit I deposit.

Wurtzite (ZnS) was tentatively identified in a polished thin section of Woodrow ore. Viewed in reflected light the wurtzite (?) is gray, with deep internal reflections, similar to sphalerite; in transmitted light it is deep amber and gives a uniaxial positive interference figure.

Covellite (CuS) was found in the Woodrow deposit, where it appears to be an alteration product of chalcopyrite.

Cobaltite (CoAsS) is associated with pyrite in two polished sections of Woodrow ore. It has chemical and physical properties consistent with those listed by Short (1940, p. 166). Both specimens contain arsenic, cobalt, and nickel (table 12, samples 1, 13). In sample 1, cobalt and arsenic are in approximately the correct proportions for cobaltite.

In milling the Jackpile ore, only a small amount of oxidizing agent (MnO_2) is used and that is used mainly to counter the reducing effect of carbonaceous material and the metallic iron (Argall, 1956, p. 48) picked up during grinding. The fact that such a small amount of oxidizing agent is needed plus the fact that the uranium is nearly 100 percent soluble in the sulfuric acid leach solution used has led metallurgists to believe that coffinite is not a major constituent of the ores (Dale Matthews, metallurgist for the Anaconda Co., oral commun., 1957). The X-ray data show clearly that coffinite is a major constituent, however, though solubility of the coffinite is an unsolved problem.

OXIDATION PRODUCTS

Most uranium deposits in the Laguna district are oxidized to some extent, and some show pervasive effects of oxidation. Because detailed studies of the oxidation of uranium deposits have been made in other parts of the Colorado Plateau (Weeks and others, 1959; Garrels and Christ, 1959; Garrels and Pommer, 1959; and Garrels and others, 1959), only general descriptions are presented here.

Hexavalent-uranium minerals observed by us in the Woodrow mine, mainly above the 100-foot level (above water table), were sulfates, silicates, and phosphates. Zippeite [$2UO_3 \cdot SO_3 \cdot 5H_2O$] or zippeitelike minerals seem to be the most abundant oxidation product in the typical high-grade Woodrow ore; uranopilite [$(UO_2)_6(SO_4)(OH)_{10} \cdot 12H_2O$] has been identified. Meta-autunite [$Ca(UO_2)_2(PO_4)_2 \cdot 2\frac{1}{2}–6\frac{1}{2}H_2O$] encrusts fractures and partings in a bone fragment. Cuprosklodowskite [$Cu(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$] occurs in parts of the deposit that are relatively rich in copper. Several other minerals were listed by Wylie (1963, p. 180).

In the Jackpile mine, oxidation products are most abundant in the south pit. Here, tyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 7–10.5H_2O$] and metatyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 5H_2O$] form small concretionary masses near the west edge of the deposit and small tabular deposits a few feet below the main ore body. The tabular layers may represent downward leaching of uranium and vanadium from the main deposit and redeposition on the mudstone beds. Tyuyamunite is also disseminated in partly oxidized ore and is present on fractures in silicified logs, mudstone, and diabase. This mineral reflects the availability of some vanadium during oxidation. The phosphates autunite [$Ca(UO_2)_2(PO_4)_2 \cdot 10–12H_2O$] and phosphuranylite [$Ca(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$] have been found in silicified logs. Autunite also has been found on fractures in mudstone and diabase, where it indicates the presence of phosphates, probably mostly apatite, in these rocks before oxidation. Uranophane [$Ca(OU_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$] is locally abundant in longitudinal joints in the chill borders of diabase sills.

The only oxidation products of uranium and vanadium found in the Sandy mine are carnotite [$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$], tyuyamunite, and metatyuyamunite; in the Chavez mine, carnotite; and in the Crackpot mine, tyuyamunite, which is associated with a small amount of fluorescent opal. In the limestone these minerals are distributed mainly along joints, but in the more permeable sandstones they are disseminated in the host rock also.

URANIUM AND VANADIUM CONTENT

Mill records provide the most representative data on the uranium and vanadium contents of the ores (table 6). Woodrow ore, which contains, on the average, more than 1 percent uranium but very little vanadium, is unique. All other ores generally contain far less uranium and considerably more vanadium. The uranium-vanadium ratio (2.7) in average Jackpile ore is probably fairly representative of the ratio in large deposits in the Jackpile sandstone. The small deposits in the Westwater Canyon, Entrada, and Todilto host rocks have a much smaller ratio (table 6).

TABLE 6.—*Uranium and vanadium contents of the ores as shown by mill records, 1950–58*

Mine	Host rock	Ore (tons)	U_3O_8 (percent)	V_2O_5 (percent)	U:V
Woodrow	Jackpile Sandstone	5,326	1.26	0.04	48.6
Jackpile	do	3,272,236	.23	.13	2.7
Windwhip	do	2,788	.31	.17	2.8
Saint Anthony	do	2,658	.20	----	----
Chavez	Westwater Canyon Member of Morrison Formation.	190	.21	.56	.6
Sandy	Entrada Sandstone	939	.12	.14	1.3
Crackpot	Todilto Formation	3,214	.13	.33	.6

Within individual deposits, uranium-vanadium ratios range greatly. In general, the uranium content ranges between much greater limits than the vanadium content, so that uranium-vanadium ratios are high in high-grade ore and low in low-grade ore. This relation is shown in figure 18, where uranium-vanadium ratios in selected samples are plotted against percentage of uranium. Samples from the Sandy and Windwhip mines were taken from bottom to top in exposed ore and laterally across curved gradational ore boundaries. The samples from the Jackpile mine include two sets of five samples each, taken vertically across exposed ore, plus many samples taken at widely spaced intervals in other parts of the open pit. The ratios plotted in figure 18 do not represent all of the samples taken, because vanadium was not determined in amounts less than 0.028 percent in samples from the Jackpile and Windwhip mines, and 0.028 and 0.056 percent in different suites of samples from the Sandy mine.

In all three mines the range of the uranium-vanadium ratio is great, but the ratio generally increases with increasing grade (fig. 18). Accordingly, vanadium tends to be more homogeneously distributed within a deposit than uranium. Within a deposit, vanadium content generally increases as uranium content increases, but much more gradually. This probably reflects the different mineralogic occurrences of the two elements. Vanadium in the relatively unoxidized deposits is largely in micaceous silicates and may partly reflect the original fairly homogeneous distribution of clay. Uranium, on the other hand, is largely in finely divided coffinite and uraninite, the distribution of which may not depend upon the distribution of any original constituent of the rock.

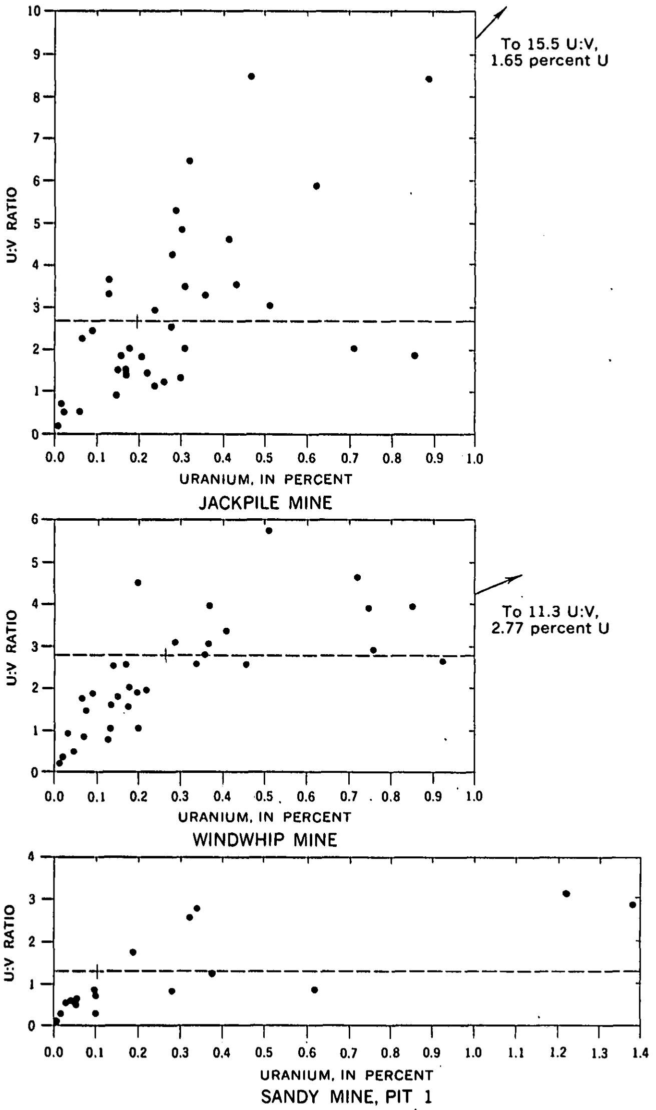


FIGURE 18.—Variations of uranium-vanadium ratio with uranium content, Jackpile, Windwhip, and Sandy mines. Dashed lines represent average ratio and grade from mill data.

MINOR ELEMENTS

Several elements in addition to uranium and vanadium, mostly present in amounts of much less than 1 percent, appear to be more abundant in the uranium deposits than in the immediately surrounding rocks. Shoemaker, Miesch, Newman, and Riley (1959, p. 35) defined intrinsic elements as those "elements whose presence in the ore is unrelated to the process of uranium mineralization," and extrinsic elements as those "elements that have been introduced by processes of or related to uranium mineralization into the body of sediment or rock that became the uranium deposit." As they pointed out, probably no single element is wholly extrinsic or intrinsic, but these terms conveniently distinguish between those elements that were largely introduced during mineralization and those that were present before mineralization. Even though we cannot compare in detail the minor elemental composition of the deposits with unmineralized sedimentary rocks well away from the deposits, the term "extrinsic" is used in this report, because many elements vary significantly with ore grade or rock darkness, and some elements can be related to specific ore minerals.

Shoemaker, Miesch, Newman, and Riley (1959) studied the elemental composition of uranium deposits in the central and northern parts of the Colorado Plateau—mostly in Utah and western Colorado. At the time of their study, the Grants and Laguna districts had not been extensively developed, and the few samples then available from these districts were not included in their study. They were primarily concerned with the elemental composition of whole deposits; accordingly, they used mill-pulp samples exclusively and treated their analytical results statistically. In this report we are concerned primarily with elemental variations within deposits; accordingly many of our samples represent observable geologic features. For these reasons, and because only a few deposits are mined in the Laguna district, quantitative comparisons cannot be made between deposits in this district and those elsewhere on the Colorado Plateau. Qualtitatively, however, similar conclusions can be drawn from the two studies.

Mill-pulp samples, which indicate to some extent the minor-element composition of typical ores, are listed in table 7 to facilitate comparisons made later in this re-

TABLE 7.—*Minor-element content of millpulp samples from six uranium deposits in the Laguna district*

[Data are in percent except as indicated. Chemical analyses by C. G. Angelo, R. R. Beins, G. T. Burrow, R. P. Cox, N. E. Crowe, Mary Finch, W. D. Goss, H. H. Lipp, E. C. Mallory, T. Miller, L. F. Rader J. S. Wahlberg, and J. E. Wilson. Semiquantitative spectrographic analyses by R. G. Havens and N. M. Conklin. 0, looked for but not detected; Tr., near threshold amount of element; <, less than number shown but standard sensitivities do not apply; ----, not looked for; M, major constituent]

Laboratory No.	Mine	Chemical analyses									Semiquantitative spectrographic analyses									
		eU	U	V_2O_5	F	P_2O_5	S	Se [1]	Zn [1]	As [1]	Si	Al	Fe	Mg	Ca	Na	K	Ti	Mn	Ag
229373 [2]	Jackpile	0.33	0.31	----	<0.002	<0.05	----	1	20	20	M	1.5	0.7	0.3	0.3	0.3	1.5	0.15	0.03	0
229375 [2]	Windwhip	.26	.28	----	----	----	----	18	10	20	M	3.0	.7	.15	.3	.15	1.5	.07	.03	0
239460 [2]	Woodrow	.87	1.16	----	.022	----	6.64	8	35	890	M	3.0	7.0	.3	.3	.7	3.0	.15	.03	0.0003
245226	Chavez	.14	.20	0.56	.009	----	.49	50	21	83	M	3.0	1.5	.7	7.0	.7	3.0	.15	.07	0
245229	Sandy (Pit 1)	.094	.10	.13	.006	.024	.08	15	12	15	M	3.0	.7	.7	M	1.5	3.0	.07	.07	0
245228	Crackpot	.071	.097	.33	.016	.011	.71	3	7	18	3.0	1.5	.3	.3	M	.3	1.5	.007	.03	0

Laboratory No.	Mine	Semiquantitative spectrographic analyses (continued)																	
		B	Ba	Be	Co	Cr	Cu	Ga	Mo	Ni	Pb	Sc	Sr	Tl	U	V	Y	Yb	Zr
229373 [2]	Jackpile	0.0015	0.03	0.00015	0.0007	0.0015	0.003	<0.0002	0.0003	[3] 0.0015	0.007	0	0.003	0	0.3	0.15	0.0007	0	0.03
229375 [2]	Windwhip	.0015	.07	.00015	.0003	.0007	.003	<.0002	.00015	[3] .0015	.007	0	.003	0	.3	.07	.003	0	.015
239460 [2]	Woodrow	0	.15	Tr.	.015	.0015	.015	Tr.	.003	.007	.03	0.0007	.015	Tr.	1.5	.015	.003	<0.001	.015
245226	Chavez	.003	.07	0	.0007	.007	.007	Tr.	.007	.0007	.003	0	.015	0	.15	.3	.003	<.002	.015
245229	Sandy (Pit 1)	Tr.	.03	0	.0015	.003	.003	Tr.	.0015	.0007	.003	0	.015	0	.07	.03	.0015	.0003	.007
245228	Crackpot	0	.015	0	0	.0015	.003	0	0	.0007	.003	0	.03	0	.07	.15	0	<.002	.003

[1] Parts per million.
[2] Spectrographic data converted from X to numerical notations.
[3] Possibly in error; not confirmed by other samples from same deposit.

port. Direct comparison must be made with caution, however, because the samples represent different grades of ore, and one sample from a deposit as large as the Jackpile can hardly be representative.

JACKPILE DEPOSIT

Semiquantitative spectrographic data for 52 samples collected from the Jackpile mine are listed in table 8 in order of increasing darkness (or shade value), which is directly proportional to the organic carbon content (fig. 22). The relations of uranium, vanadium, manganese, barium, chromium, lead, and copper contents to darkness are most readily observed diagrammatically. In figure 19 the ranges and arithmetic averages of the contents of these elements are shown for each shade value. In each diagram, the three darkest shade values and the 7.5 value are least reliable, as they are represented by only one sample each.

In summary, uranium, vanadium, manganese, boron, beryllium, cadmium, cobalt, copper, germanium, lanthanum, lead, yttrium, ytterbium, and possibly chromium and gallium show varying degrees of correlation with the darkness of the rock. Barium appears to be inversely proportional to darkness, and iron, magnesium, calcium, titanium, strontium, and zirconium do not exhibit a detectable correlation. Strontium is commonly most abundant where calcium is most abundant.

Some elements that correlate with darkness are distributed among specific minerals in the ore (table 9). In table 9, one separate of vanadium clay is compared with three of uraniferous carbonaceous matter. Aluminum, potassium, uranium, and vanadium show the expected distribution. Of the minor elements that are concentrated in ore, beryllium, cadmium, cobalt, and chromium are most abundant in the vanadium clay. Lead expectably is most abundant in the uraniferous carbonaceous matter, and yttrium and ytterbium may also be similarly concentrated. Other elements show no recognizable correlation.

WINDWHIP DEPOSIT

Part of the Windwhip deposit was sampled in detail to determine what elements are associated with the ore, and if there is any peculiar distribution of minor elements relative to different parts of the deposit and the surrounding sandstone (table 10; fig. 20). Most samples were taken at about 1-foot intervals vertically and horizontally across the deposit: three ($2C_1$, $2C_2$, $2C_3$, fig. 20) were taken across the banded, convex part, and 10 were taken at 2-foot intervals between the top of the deposit and the base of the Dakota Sandstone.

A close correlation can be seen between uranium content and the visible features of the deposit (fig. 20). The highest grade part of the deposit is associated with dark rock directly in the center of the deposit; visibly sharp color boundaries are associated with abrupt changes of uranium content, and gradational color boundaries are associated with gradual changes of uranium content.

To illustrate the relations between uranium and the other minor elements, samples are listed in table 10 in order of increasing uranium content. Darkness of material is not used as the basis here because it has been changed somewhat by oxidation. Correlations of vanadium, calcium, manganese, beryllium, cobalt, lead, yttrium, ytterbium, and possibly cadmium, germanium, chromium, and molybdenum with uranium content can be seen in table 10. Of the arithmetic averages of elements (table 11), manganese, calcium, and copper show marked correlations with uranium. Strontium, titanium, and magnesium correlate somewhat.

Iron and titanium show peculiar distribution patterns. Iron appears to be deficient in a thin zone directly above the deposit. Samples 7H, 7I, 1J, 8I, and 8J contain either 0.03 or 0.07 percent iron, whereas all but one of the other samples contain 0.15 percent or more iron (fig. 20; table 10). Titanium is most abundant in samples 3B and 3C (fig. 20; table 10), which were obtained from a gradational concave junction between the upper and lower layers shown in the right-hand side of figure 20.

WOODROW DEPOSIT

Because the Woodrow deposit has a pipelike form and is composed of contrasting types of ore—massive sulfide, massive coffinite, and mixtures of the two—no attempt was made to compare "typical" ore with "typical" unmineralized rock. Instead, the minor-element associations are shown by tabulating contrasting types of materials (table 12). In table 12, the upper 7 specimens are of various types of ore, and the lower 10 are mineral separates from the same and other similar ore specimens.

TABLE 8.—*Distribution of minor elements, in percent, relative*

[Color shades are according to "Rock-Color Chart" (Goddard and others, 1948). Percentages determined by semiquantitative spectrographic analysis except as

Shade	Very light gray							Light gray			
	8							7.5	7		
U [1]	0.074	0.011	0.017	0.050	0.007	0.055	0.040	0.030	0.011	0.033	0.03
V	.003	[1] .048	.03	.07	.003	.007	.003	.003	.015	.03	.003
Fe	.15	.3	.3	.3	.15	.3	.15	.3	.3	.7	.15
Mg	.03	.07	.07	.07	.07	.07	.07	.07	.03	.07	.07
Ca	.15	.7	.07	.15	.03	.07	.015	.015	.07	.15	.07
Ti	.07	.07	.15	.15	.07	.15	.03	.15	.03	.15	.03
Mn	.0015	.0015	.003	.003	.0015	.0015	.0015	.0015	.007	.003	.0015
B	0	0	0	0	0	0	0	0	0	0	0
Ba	.3	.15	.15	.15	.15	.15	.15	.07	.07	.07	.07
Be	0	0	0	0	0	0	0	0	0	0	0
Cd	0	0	0	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0
Cr	.00015	.00015	.00015	.00015	.00015	.00015	.00015	.00015	.00015	.00015	.00015
Cu	.0007	.0007	.0003	.0003	.0003	.00015	.0015	.0003	.0007	.0015	.00015
Ga	0	0	0	0	0	0	0	0	0	0	0
Ge	0	0	0	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0	0	0	0	0
Pb	.0015	.0015	.0015	.003	.0015	.0015	.0007	.0007	.0015	.0015	.0007
Sr	.007	.003	.003	.003	.003	.003	.0015	.0015	.0015	.003	.0007
Y	0	0	0	0	0	.0007	0	0	0	0	0
Yb	0	0	0	<.001	0	.00015	0	0	0	0	0
Zn	.007	.007	.03	.007	.015	.015	.007	.007	.003	.015	.003

Shade	Medium gray—Continued										
	5.5		5								
U [1]	0.26	0.28	0.060	0.30	0.89	0.17	0.43	0.28	0.51	0.32	0.24
V	[1] .224	[1] .112	[1] .112	[1] .229	[1] .106	[1] .112	[1] .123	[1] .068	[1] .168	[1] .050	[1] .084
Fe	.3	.3	.7	.7	.3	.7	.3	.15	.7	.15	.3
Mg	.15	.07	.15	.3	.07	.3	.15	.07	.15	.03	.03
Ca	.15	.15	.15	.15	.7	3.0	.07	.15	.07	.3	.07
Ti	.07	.15	.07	.15	.15	.15	.07	.07	.15	.07	.07
Mn	.015	.007	.007	.015	.007	.07	.007	.007	.007	.003	.003
B	0	.003	0	0	0	0	.003	0	.003	0	0
Ba	.03	.03	.07	.15	.07	.07	.03	.03	.07	.03	.015
Be	.00015	0	0	.0003	0	0	.00015	0	.00015	0	0
Cd	0	0	0	0	0	0	0	0	0	0	0
Co	<.002	<.002	0	<.001	<.001	<.001	<.005	<.002	<.002	<.002	<.002
Cr	.00015	.0007	.00015	.0007	.0003	.0003	.00015	.00015	.0007	.00015	.003
Cu	.0007	.0007	.0007	.0007	.0003	.0007	.0007	.0003	.0007	.0007	.0007
Ga	Tr.	0	0	0	0	0	Tr.	0	Tr.	0	0
Ge	0	0	0	0	0	0	0	0	<.005	0	0
La	0	0	.003	0	0	0	0	0	0	0	0
Pb	.015	.003	.007	.003	.007	.003	.007	.0015	.007	.003	.007
Sr	.007	.0015	.007	.015	.003	.015	.0015	.0015	.003	.0015	.0015
Y	0	.003	.0015	.0007	0	.0007	.0015	0	.0015	.0015	.0015
Yb	0	0	<.001	<.001	<.001	<.001	0	<.0005	0	.00015	<.001
Zn	.015	.03	.015	.007	.015	.015	.007	.007	.015	.015	.015

[1] Determined by chemical methods. Analysts: C. P. Angelo, G. T. Burrow, E. J. Fennelly, H. H. Lipp, J. P. Schuch.

to darkness of material in Jackpile uranium deposit

indicated; analyst: R. G. Havens. 0, looked for but not detected; Tr., near threshold amount of element; <, less than number shown but standard sensitivities do not apply]

Light gray—Continued			Medium light gray								Medium gray			
7			6.5		6						5.5			
0.10	0.006	0.02	0.035	0.093	0.027	0.062	0.29	0.14	0.21	0.11	0.15	0.31	0.30	0.13
.015	.007	[1] .028	.003	[1] .039	[1] .05	[1] .028	[1] .056	[1] .129	[1] .117	.007	[1] .162	[1] .09	[1] .062	[1] .039
.7	.7	1.5	.3	.3	.3	.7	.3	.3	.3	.15	1.5	.3	.3	.3
.15	.15	.3	.07	.07	.07	.15	.07	.07	.07	.03	.15	.07	.07	.07
.03	.7	3.0	.03	.07	.15	.07	.07	.07	.15	.3	.15	.03	.07	.15
.15	.15	.03	.15	.15	.07	.07	.07	.07	.07	.07	.15	.07	.07	.07
.003	.015	.03	.0015	.0015	.003	.007	.003	.007	.007	.003	.015	.007	.007	.007
0	0	0	0	0	0	0	0	.003	.003	0	0	.003	.003	.015
.15	.15	.15	.07	.03	.15	.15	.03	.03	.07	.03	.15	.03	.03	.03
0	0	0	0	0	0	0	0	.00015	0	0	.00015	0	.00015	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	<.002	<.002	<.002	<.002	<.001	<.002	<.002	<.002
.0003	.00015	.00015	.00015	.00015	.00015	.00015	.00015	.00015	.0003	.00015	.00015	.00015	.0003	.00015
.0007	.00015	.0007	.00015	.0007	.0003	.0007	.0007	.0007	.0007	.0007	.0007	.0007	.0007	.0007
0	0	0	0	0	0	0	0	0	Tr.	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.003	.0015	.003	0	0	.003	.003	.0015	.007	.007	.0015	.015	.003	.007	.0015
.003	.003	.015	.0007	.0015	.003	.007	.0015	.0015	.003	.0015	.007	.0015	.003	.007
0	0	.0007	0	.0015	.0015	0	.0015	0	0	.0015	.0015	0	0	.0015
0	0	.00015	0	.0003	.0003	<.001	.0003	0	0	.0007	<.001	.00015	<.0005	.0003
.015	.015	.007	.015	.015	.007	.015	.007	.015	.015	.007	.007	.015	.007	.015

Medium gray—Con.		Medium dark gray										Dark gray		
5		4.5			4							3.5	3	2.5
1.65	0.16	0.15	0.22	0.31	0.36	0.18	0.41	0.47	0.17	0.62	0.67	0.71	0.85	0.51
[1] .106	[1] .09	[1] .101	[1] .157	[1] .157	[1] .112	[1] .090	[1] .050	[1] .056	[1] .123	[1] .106	[1] .045	[1] .347	[1] .205	.03
.3	.3	.3	.3	.15	.3	.7	.3	.3	1.5	.3	.15	.7	.3	.7
.07	.07	.07	.07	.07	.07	.15	.07	.15	.3	.07	.03	.07	.07	.15
.15	.15	.03	.07	.07	.15	.15	.7	.3	1.5	.07	.07	.15	.15	.03
.07	.15	.03	.07	.07	.07	.15	.15	.07	.07	.07	.07	.07	.07	.07
.007	.007	.003	.007	.007	.007	.007	.007	.007	.03	.007	.007	.015	.015	.007
0	0	0	.003	0	0	.003	0	0	0	0	0	.003	0	0
.07	.03	.07	.03	.03	.07	.15	.15	.07	.07	.03	.03	.03	.03	.07
.00015	0	0	.00015	.00015	0	0	0	0	0	.00015	0	.0003	.0003	0
<.05	0	0	0	0	0	0	0	0	0	<.05	<.05	<.05	<.05	0
<.005	<.002	<.001	<.002	<.002	<.001	<.001	<.001	<.001	<.001	<.005	<.002	<.005	<.005	<.001
.00015	.0007	.00015	.0003	.0007	.0003	.00015	.00015	.0007	.0003	.0003	.00015	.0015	.00015	.00015
.0007	.0007	.0007	.0015	.0015	.0007	.0003	.0007	.0015	.0003	.0007	.0015	.0015	.0015	.0007
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<.005	0	0	0	0	0	0	0	0	0	<.005	<.005	<.005	<.005	0
.003	0	0	.003	0	0	0	.003	.003	0	.003	.003	0	0	.003
.015	.003	.003	.015	.003	.007	.007	.007	.015	.007	.007	.007	.007	.007	.03
.0015	.0015	.003	.007	.0015	.003	.007	.003	.007	.015	.0015	.0015	.003	.0015	.007
.0015	.0015	0	0	.0015	0	0	.0007	.003	0	0	.0015	0	0	.0015
<.001	<.005	0	0	<.001	<.001	<.001	<.001	<.001	<.001	<.005	.0003	0	0	<.001
.007	.007	.015	.007	.007	.015	.015	.015	.015	.015	.007	.03	.015	.007	.015

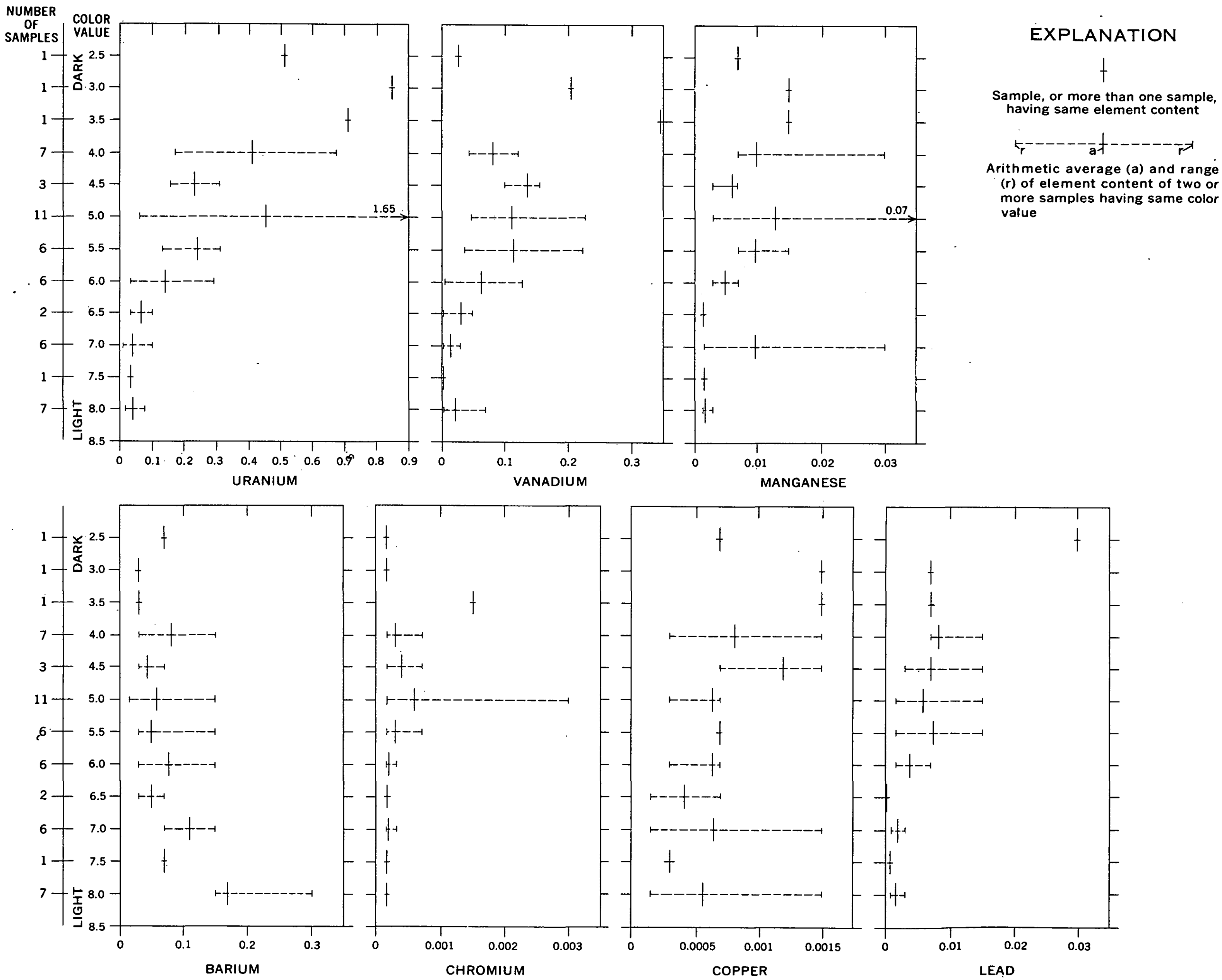


Figure 19.—Distribution of minor elements, in percent, relative to color, Jackpile uranium deposit. Color values taken from "Rock-Color Chart" (Goddard and others, 1948).

TABLE 9.—*Minor-element content, in percent, of four samples from the Jackpile deposit*

[Analyses by N. M. Conklin, by semiquantitative spectrographic method, except as noted. 0, looked for but not detected; <, less than number shown, but standard sensitivities do not apply; ----, not looked for]

Sample	Si	Al	Fe	Mg	Ca	Na	K	Ti	Mn	Ba	Be	Cd	Co
1	----	0.15	0.7	0.07	0.3	----	0	0.07	0.3	0.03	0	0	<0.002
2	----	.07	.15	.07	.7	----	0	.03	.07	.0015	0	0	<.002
3	----	.15	.3	.3	1.5	----	0	.015	.03	.03	0	0	<.002
4	----	7.0	3.0	.7	.7	----	7.0	.07	.07	.07	0.0015	<0.1	.007

Sample	Cr	Cu	Mo	Ni	Pb	Sn	Sr	U	U [1]	V	Y	Yb	Zr
1	0.0015	0.15	0.007	0.015	0.7	0	0.03	3.0	3.6	0	0.07	0.007	0.015
2	0	.003	0	0	.07	0	.007	7.0	8.1	0	0	0	0
3	.0015	.007	.007	0	.15	0	.07	7.0	5.4	0.07	.07	.007	0
4	.015	.15	.007	0	.015	.015	.015	1.5	----	7.0	0	----	0

[1] Determined fluorimetrically by E. J. Fennelly.

DESCRIPTION OF SAMPLES

1. Lab. No. 279505; uraniferous carbonaceous matter from ring fault of collapse structural feature.
2. Lab. No. 279506; same as sample 1.
3. Lab. No. 279507; uraniferous carbonaceous matter from concentration around clay gall.
4. Lab. No. 270537; vanadium clay from veinlet in mineralized silicified log.

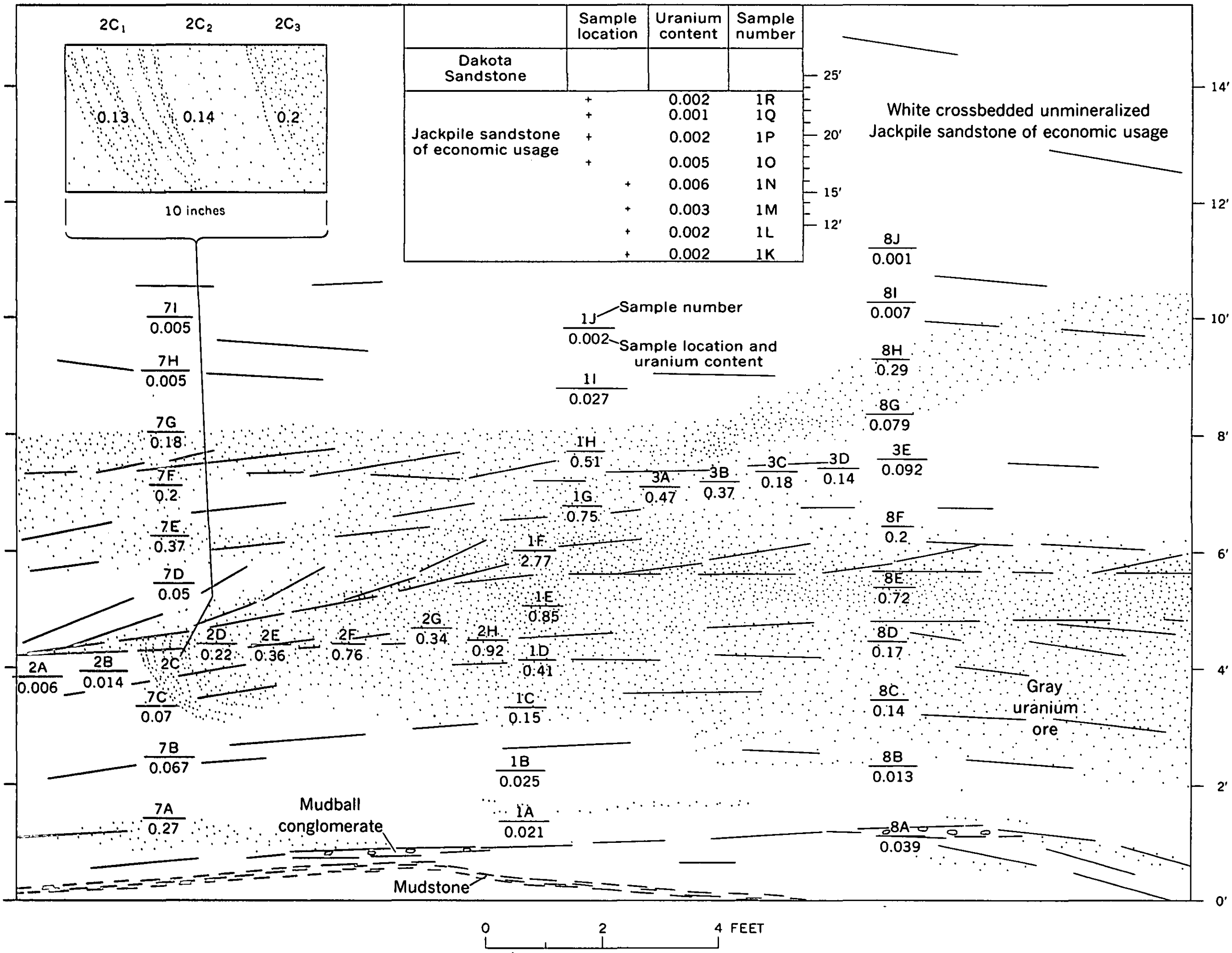


FIGURE 20.—Part of Windwhip deposit, showing distribution of samples in table 10, and uranium content, in percent. Top-center inset shows spacing of samples 1K to 1R relative to base of Dakota Sandstone, which is not shown in the diagram.

TABLE 10.—*Distribution of minor elements relative*

[Percentages determined by semiquantitative spectrographic analysis except as indicated; analyst: P. J. Dunton. 0, looked for but not detected;

Laboratory No. (256–)	302	267	268	266	262	261	260	263	265	292	291	264
Field No.	8J	1Q	1R	1P	1L	1K	1J	1M	1O	7I	7H	1N
U [2]	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.003	0.005	0.005	0.005	0.006
V	.003	0	.0015	.003	.003	.007	.007	.007	.003	.007	[2] .028	.003
Fe	.03	.7	.15	.3	.15	.15	.03	.15	.7	.07	.07	.7
Mg	.015	.07	.07	.07	.03	.03	.03	.03	.07	.03	.03	.07
Ca	.03	.03	.07	.07	.03	.03	.03	.03	.07	.03	.3	.07
Ti	.03	.07	.15	.07	.07	.07	.15	.07	.07	.07	.03	.07
Mn	0	.0015	.0007	.003	.0007	.0015	.0007	.0015	.015	.0015	.0015	.003
B	0	.003	.003	.003	0	.003	0	0	0	0	0	.003
Ba	.015	.03	.03	.03	.03	.07	.03	.03	.07	.03	.07	.03
Be	0	0	0	0	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0	0
Cr	0	.00015	.0007	.00015	0	.0015	0	0	.00015	0	0	.00015
Cu	0	.0015	.00015	.0003	.0003	.0015	.00015	.0007	.0007	.0003	.0003	.0003
Mo	0	.0007	0	.0007	0	0	0	0	0	0	0	0
Pb	0	0	0	0	0	0	0	0	.003	0	0	0
Sr	.0003	.0015	.0015	.0015	.0003	.0015	.0003	.0015	.0015	.0015	.0015	.0015
Y	0	0	0	0	0	0	0	0	.0015	0	0	0
Yb	0	0	0	0	0	0	0	0	0	0	0	0
Zr	.007	.007	.03	.007	.015	.015	.007	.007	.007	.007	.003	.007
Cd	0	0	0	0	0	0	0	0	0	0	0	0
Ga	0	0	0	0	0	0	0	0	0	0	0	0
Ge	0	0	0	0	0	0	0	0	0	0	0	0
C [3]	----------	----------	----------	----------	----------	.08	----------	----------	----------	----------	----------	----------

Laboratory No. (256–)	272	295	253	296	281	290	289	298	273	274	284	300
Filed No.	$2C_2$	8C	1C	8D	3C	7G	7F	8F	$2C_3$	2D	7A	8H
U [2]	0.14	0.14	0.15	0.17	0.18	0.18	0.20	0.20	0.20	0.22	0.27	0.29
V	[2] .14	[2] .056	[2] .084	[2] .067	[2] .09	[2] .117	[2] .106	[2] .045	[2] .196	[2] .112	.015	[2] .095
Fe	.15	.07	.15	.15	.15	.15	.15	.15	.15	.15	.3	.3
Mg	.07	.03	.07	.03	.03	.07	.03	.03	.07	.07	.07	.03
Ca	.07	.07	.15	.07	.07	.15	.15	.3	.15	.15	.15	.07
Ti	.15	.07	.07	.15	.3	.07	.07	.03	.07	.07	.07	.07
Mn	.007	.003	.007	.007	.003	.015	.007	.0015	.007	.007	.003	.007
B	0	0	0	0	0	0	0	0	0	.003	0	0
Ba	.015	.015	.03	.03	.015	.03	.015	.07	.015	.03	.03	.03
Be	0	0	0	0	0	.00015	0	0	0	.00015	0	0
Co	0	.0003	0	.0003	.0003	0	.0003	.0003	.0003	.0003	.0007	0003
Cr	.00015	0	.00015	.00015	.00015	.00015	.003	0	.00015	0	.00015	.00015
Cu	.0007	.00015	.00015	.0003	.00015	.0015	.0007	.0003	.0015	.0007	.0007	.0007
Mo	0	0	0	0	.0007	.003	.007	0	0	0	0	.0007
Pb	0	0	0	0	.015	.015	.007	.003	0	.0015	0	.0015
Sr	.0015	.0015	.0015	.0015	.0015	.003	.0015	.0015	.0007	.0015	.0015	.0015
Y	0	0	0	0	0	.003	.0015	0	0	.003	.0015	.0015
Yb	0	0	0	0	0	.0007	0	0	0	.0007	0	0
Zr	.007	.015	.007	.015	.015	.007	.007	.007	.03	.007	.015	.007
Cd	0	0	0	0	0	0	0	0	0	0	0	0
Ga	0	0	0	0	0	.00015	0	0	0	0	0	0
Ge	0	0	0	0	0	0	0	0	0	0	0	0
C [3]	----------	----------	----------	.19	----------	----------	----------	----------	----------	.26	----------	.25

[1] Selected specimens not shown in figure 20.
[2] Determined by chemical methods. Analysts: G. S. Erickson, E. J. Fennelly, W. D. Goss, Claude Huffman, and H. H. Lipp.
[3] Determined by tube furnace-gasometric method; analyst: Wayne Mountjoy.

to uranium content, in percent, Windwhip deposit

Tr., near threshold amount of element; <, less than number shown, but standard sensitivities do not apply; ----, not determined]

269	301	294	270	251	252	259	293	287	285	286	299	283	271	282
2A	8I	8b	2b	1A	1B	1I	8A	7D	7B	7C	8G	3E	$2C_1$	3D
0.006	0.007	0.013	0.014	0.021	0.025	0.027	0.039	0.050	0.067	0.070	0.079	0.092	0.13	0.14
.015	.015	[2].067	.015	[2].028	[2].067	[2].028	.015	[2].101	[2].039	[2].084	[2].056	[2].050	[2].168	[2].090
.07	.07	.3	.15	.15	.15	.3	.3	.3	.15	.15	.15	.15	.15	.15
.03	.03	.07	.03	.07	.07	.03	.07	.15	.07	.07	.03	.03	.07	.03
.07	.15	.15	.07	.15	.07	.07	.03	.15	.07	.15	.07	.07	.15	.07
.07	.07	.07	.07	.15	.07	.07	.07	.07	.07	.07	.03	.03	.07	.07
.0007	.0003	.003	.0007	.003	.003	.003	.003	.007	.0015	.003	.003	.0015	.007	.003
0	0	0	.003	0	0	0	0	.003	.003	.003	0	0	.003	0
.03	.03	.03	.015	.03	.03	.15	.03	.03	.03	.015	.03	.07	.015	.03
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	.00015	0	.00015	.00015	.00015	.00015	.0003	.00015	.00015	.00015	.00015	.00015	.00015
.00015	0	.0007	.00015	.0007	.0007	.0003	.0007	.0003	.0003	.0003	.00015	.0007	.0015	.00015
0	0	0	0	0	0	.0007	0	.003	0	0	0	0	0	0
0	0	.0015	0	0	0	.003	0	.015	0	0	0	0	0	0
.0007	.0007	.0015	.0003	.0015	.0015	.0015	.0015	.003	.0015	.0015	.0015	.0015	.0015	.0015
0	0	0	0	0	0	0	0	0	0	0	0	0	.0015	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.015	.015	.03	.007	.015	.007	.007	.007	.015	.015	.007	.007	.003	.007	.015
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	.0003	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
----	----	----	.10	----	.08	----	----	----	----	----	----	.11	----	----

277	275	280	288	254	279	258	297	257	276	255	218	278	217	256
2G	2E	3B	7E	1D	3A	1H	8E	1G	2F	1E	([1])	2H	([1])	1F
0.34	0.36	0.37	0.37	0.41	0.47	0.51	0.72	0.75	0.76	0.85	0.91	0.92	1.51	2.77
[2].134	[2].134	[2].095	[2].123	[2].123	[2].185	[2].09	[2].157	[2].196	[2].263	[2].218	[2].134	[2].347	[2].196	[2].246
.15	.15	.3	.15	.15	.3	.3	.3	.3	.3	.7	.15	.3	.15	.3
.03	.07	.03	.03	.07	.07	.07	.07	.07	.07	.07	.07	.07	.15	.15
.15	.3	.15	.15	.3	.15	.15	.15	.3	.3	.3	.3	.3	.3	.7
.07	.07	.3	.07	.07	.03	.07	.07	.15	.07	.07	.07	.03	.07	.07
.007	.015	.007	.007	.015	.007	.007	.015	.015	.015	.015	.007	.015	.015	.015
0	.003	0	.003	.003	.003	0	0	.003	.003	.003	0	0	0	.003
.015	.03	.03	.03	.03	.03	.07	.03	.03	.03	.03	.03	.03	.03	.07
.00015	.00015	0	0	.0003	.00015	0	.00015	.00015	.00015	.0003	.00015	.00015	.0003	.0003
.0007	.0007	.0007	.0007	.0015	.0015	.0015	.0015	.0015	.0015	.0015	<.005	.0015	<.002	.003
.00015	.00015	.0003	.00015	.0003	.0003	.00015	.00015	.00015	.0003	.00015	.0003	.0003	.0003	.0003
.00015	.0007	.00015	.0003	.0007	.0007	.0007	.0007	.0007	.0007	.0015	.0015	.0007	.0015	.0007
0	0	.0007	.0007	0	0	.007	0	.0015	0	.007	.0015	0	0	.0007
.003	.003	.015	0	.0015	.003	.007	.003	.015	.007	.015	.007	.015	.007	.015
.0015	.0015	.003	.0015	.0015	.003	.0015	.0015	.0015	.0015	.003	.003	.0015	.003	.003
0	.003	0	0	.003	0	0	.003	.0015	.003	.0015	.0015	.0015	.015	.0015
0	.0007	0	0	.0007	0	0	.0007	0	.0007	0	0	0	0	0
.007	.007	.03	.007	.015	.007	.007	.015	.015	.007	.015	.007	.007	.007	.007
0	0	0	0	0	0	0	0	0	0	0	<.05	0	<.05	0
	0	0	0	0	0	0	0	0	0	0	Tr.	0	Tr.	0
0	0	0	0	0	0	0	0	0	0	0	<.005	0	<.005	0
----	----	.11	----	.34	----	----	----	.28	.28	----	----	----	----	----

TABLE 11.—*Arithmetic averages, in percent, of some elements in Windwhip deposit*

[Data are from table 10]

U	Fe	Mg	Ca	Ti	Mn	Ba	Cu	Sr	Zr
0.001–0.010	0.24	0.043	0.072	0.076	0.0023	0.038	0.00045	0.0011	0.0011
0.01–0.1	.20	.063	0.095	.070	.0029	.042	.00045	.0015	.0011
>0.1	.22	.062	.200	.090	.0086	.031	.00071	.0018	.0011

TABLE 12.—*Minor-element content of selected samples*

[Data are in percent except as indicated: Chemical analyses by C. P. Angelo, G. T. Burrow, Claude Huffman, R. P. Cox,
[0, looked for but not detected; Tr., near threshold amount of element; <, less than number

Sample	Chemical analyses					Semiquantitative spectrographic analyses																	
	eU	U	V_2O_5	Se [1]	As [1, 2]	Si	Al	Fe	Mg	Ca	Na	K	Ti	P	Mn	Ag	As	B	Ba	Be	Bi	Ce	Co
Rock samples																							
1	16.9	18.97	<0.1	30	8100	3.0	0.7	M	0.15	3.0	0	0	0.03	0	0.015	0	1.5	0	1.5	0.00015	0	0	0.7
2	1.5	2.27	<.1	------	------	M	3.0	1.5	.07	.15	.7	1.5	.07	0	.007	0	0	0	.03	.00015	0	0	.015
3	1.0	1.22	<.1	------	------	M	.7	M	.03	.3	.3	.7	.03	0	.007	.00015	0	0	.015	0	0	0	.03
4	.11	.12	<.1	------	------	M	7.0	1.5	.7	.3	1.5	3.0	.15	0	.015	0	0	.003	.03	.0003	0	0	<.002
5	.12	.12	<.1	------	------	M	3.0	7.0	.03	.15	1.5	3.0	.03	0	.007	0	0	0	.07	0	0	0	0
6	.45	.68	<.1	------	------	1.5	.15	.7	.03	M	.3	0	.007	7.0	.03	.0007	0	0	.03	.00015	0	.07	<.002
7	.088	.080	<.1	------	------	M	3.0	M	.3	.3	.3	.7	.07	0	.007	0	.3	0	.15	0	0	0	.003
Mineral separates																							
8	------	------	------	------	------	0.7	1.5	1.5	0.03	0.3	<0.2	0	0.3	0	0.015	0	0	0	0.007	0	0	0	0.15
9	------	------	------	------	------	------	1.5	7.0	.15	.3	------	0	.07	0	.03	.003	.7	0	.03	0	0	0	.15
10	------	------	------	------	------	1.5	1.5	3.0	.07	.7	0	0	.15	0	.007	0	.15	0	.007	0	<.005	0	.15
11	------	------	------	------	------	------	.07	.7	.03	7.0	------	0	.03	3.0	.03	.003	0	0	.007	0	0	0	.015
12	------	------	------	6	1000	3.0	.7	M	.015	<.05	0	0	.015	0	.03	0	.7	0	.03	0	0	0	.15
13	------	------	------	10	------	3.0	.7	M	.03	.15	0	0	.03	0	.003	0	3.0	0	.007	0	0	0	.3
14	------	------	------	2	------	.7	.07	M	<.005	<.05	0	0	.007	0	.007	0	.3	0	.07	0	0	0	0
15	------	------	------	1	2000	1.5	.07	M	<.005	<.05	0	0	.003	0	.003	0	.3	0	.7	0	0	0	0
16	------	------	------	.5	1000	1.5	.3	M	<.005	<.05	0	0	.015	0	.0015	0	.15	0	.003	0	0	0	.007
17	------	------	------	<.5	2000	.3	.07	M	<.005	.15	0	0	0	0	.07	0	.3	0	.003	0	0	0	0

[1] Parts per million.
[2] Arsenic data approximate; too much arsenic for colorimetric method.

DESCRIPTION OF SAMPLES

1. Lab. No. 239604; vug filling in broken mudstone; contains pyrite, coffinite, barite and traces of cobaltite, galena, wurtzite(?).
2. Lab. No. 250800; sandstone impregnated with pyrite, coffinite, and a small amount of chalcopyrite.
3. Lab. No. 250801; same as sample 2.
4. Lab. No. 250802; broken mudstone with trace amounts of coffinite and pyrite.
5. Lab. No. 250804; coarse arkose with disseminated pyrite and marcasite and a trace of coffinite.
6. Lab. No. 250803; bone fragment; apatite is major constituent, but detrital silicates and pyrite and coffinite are present.

The Woodrow deposit is unique in the district with respect to its high uranium and low vanadium contents (table 6), and the mill-pulp sample of Woodrow ore (table 7) is richer than the others with respect to iron, sulfur, arsenic, cobalt, copper, zinc, barium, nickel, and lead. Further, silver, scandium, and tellurium were detected only in the Woodrow ore. The high sulfur and iron contents (table 1) reflect abundant pyrite and marcasite. Barium and copper are attributable to galena. Where arsenic and cobalt are about equally abundant in the same specimen (samples 1 and 10, table 12), they are attributable to cobaltite. More commonly, however (samples 7, 9, 12, 13, 14, 15, and 17, table 12), arsenic is too abundant relative to cobalt for it to be attributed to stoichiometric cobaltite and may be in solid solution in pyrite, which Fleischer (1955, p. 999) reported is possible. The high phosphorus and calcium contents of specimens 6 and 11 are attributable to the apatite that makes up the bone fragment.

Other minor elements are not attributable to identified mineral species, but many seem to be associated either with the sulfides or with the uraniferous carbonaceous matter. Silver seems to be associated with uraniferous carbonaceous matter but not with sulfides. Beryllium was detected in four ore specimens but not in any of the mineral separates. Chromium was detected in two separates of uraniferous carbonaceous matter but not in the sulfide separates; the highest chromium contents are in impure ore samples. Molybdenum does not appear to be systematically associated with any particular component of the ore. Nickel shows a distribution that is nearly proportional to cobalt and is probably contained in cobaltite. Lead expectably correlates with uranium. Strontium appears to correlate with calcium, which in turn partly reflects the distribution of calcite and apatite (bone fragment). The uranium in sulfide separates 12 and 13 (table 12) represents impurities of coffinite.

The bone fragment (sample 6, table 12) is of particular interest because it contains cerium, dysprosium, erbium, gadolinium, lanthanum, neodymium, yttrium, and ytterbium. These rare-earth elements have a strong affinity for phosphorous (Rankama and Sahama, 1950, p. 518).

PIT I DEPOSIT, SANDY MINE

Samples collected from below, above, and within the relatively unoxidized parts of the Pit I deposit are listed in table 13 in order of increasing uranium content. Vanadium, iron, magnesium, beryllium, cobalt, lead, and yttrium definitely correlate with uranium. As gallium, germanium, and lanthanum were detected only in the highest grade samples, their enrichment in the ore seems certain. As boron and molybdenum are absent in the low-grade material (less than 0.008 and 0.003 percent uranium, respectively), these elements may be enriched in the ore. Arithmetic averages of barium, copper, titanium, and nickel contents (tabulated below) *and mineral separates from the Woodrow deposit*

W. D. Goss, E. C. Mallory, J. E. Wilson, and J. S. Wahlberg. Spectrographic analyses by J. C. Hamilton and N. M. Conklin. shown but standard sensitivities do not apply; --, not looked for; M, major constituent]

Cr	Cu	Dy	Er	Ga	Gd	La	Mo	Nb	Nd	Ni	Pb	Sc	Sr	Tl	U	V	Y	Yb	Zr	Sn
Semiquantitative spectrographic analyses—Continued																				
Rock samples—Continued																				
0	0.015	0	0	0	0	0	0.015	0	0	0.15	0.3	0	0.03	0.03	M	0.3	0.15	0	0	0
.003	.15	0	0	0	0	0	.0015	0	0	.007	.03	0	.0015	0	1.5	.003	.015	.0015	.007	0
.00015	.07	0	0	0	0	0	.007	0	0	.007	.015	0	.0015	.015	.7	0	.007	.0015	.007	0
.003	.0015	0	0	.0015	0	0	.0007	0	0	.0007	.003	.0007	.03	0	.15	.003	.003	.0007	.015	0
.00015	.0015	0	0	0	0	0	.0003	0	0	.0007	.003	0	.007	0	.15	0	.007	.0007	.003	0
.0015	.003	.03	.015	0	.015	.07	.0015	0	.07	0	.015	0	.3	0	.7	.003	.15	.015	.015	0
.00015	.0015	0	0	0	0	0	.003	Tr.	0	.003	.003	0	.015	Tr.	.07	.005	.0015	.0003	.007	0
Mineral separates—Continued																				
0.0007	0.3	0	0	0	0	0.015	0.007	0	0	0.03	0.07	0	0.0007	0	7.0	0.007	0.15	0.03	0.03	0
0	7.0	0	0	0	0	0	.015	0	0	.07	.7	0	.015	0	M	.03	.07	.007	.015	0
.0007	1.5	0	0	0	0	0	.03	0	0	.07	.15	0	0	0	M	.015	.03	.003	.015	0
0	.03	0	0	0	0	0	0	0	0	0	.07	0	.07	0	3.0	.015	.15	.03	.15	0
0	.15	0	0	0	0	0	.015	0	0	.03	.07	0	0	0	.7	0	0	0	.0015	0
0	.15	0	0	0	0	0	.007	0	0	.07	.03	0	0	0	1.5	0	0	0	.007	0
0	.003	0	0	0	0	0	.007	0	0	0	.003	0	0	0	0	0	0	0	.007	0
0	.007	0	0	0	0	0	.007	0	0	0	0	0	.007	0	0	0	0	0	0	0.007
0	.003	0	0	0	0	0	.015	0	0	.003	0	0	0	0	0	0	0	0	0	0
0	.003	0	0	0	0	0	.007	0	0	0	0	0	0	0	0	0	0	0	0	0

7. Lab. No. 250805; gray mudstone with pyrite in fractures.
8. Lab. No. 256491; coffinite-bearing carbonaceous material separated from sample 2.
9. Lab. No. 256494; coffinite-chalcopyrite-bearing carbonaceous material separated from sample 3.
10. Lab. No. 256525; uraniferous carbonaceous material separated from sample like sample 2.
11. Lab. No. 256492; impure coffinite-bearing carbonaceous material from veinlets in sample 6.
12. Lab. No. 256531; pyrite separated from sample similar to sample 2.
13. Lab. No. 256532; pyrite separated from sample 3.
14. Lab. No. 256529; pyrite separated from sample 5.
15. Lab. No. 256533; pyrite separated from replacement of sandstone by pyrite.
16. Lab. No. 256530; pyrite separated from sandstone.
17. Lab. No. 256528; pyrite separated from pyrite-calcite-dolomite vug filling.

show less conspicuous correlations with uranium content, though the increases of chromium, copper, and titanium may not be significant.

Element	*Average content (percent)* Samples containing less than 0.01 U	Samples containing more than 0.01 U
Ba	0.033	0.065
Cu	.0019	.0024
Ni	.0007	.0019
Cr	.0011	.0012
Ti	.05	.07

Four mineral separates (table 14) show the mineralogic distribution of some of the minor elements. Iron in the coffinite concentrate (sample 2) probably reflects pyrite impurities. Aluminum, potassium, and magnesium are most abundant in the vanadium clays; the association of magnesium with this deposit (table 13) and not with the Jackpile and Windwhip deposits may reflect the greater abundance of vanadium-bearing clay in the Pit I deposit. Cadmium was detected only in vanadium clay (sample 4). Lead and chromium are most abundantly associated with coffinite. The uraniferous carbonaceous matter contains a large suite of rare-earth elements: cerium, dysprosium, erbium, gadolinium, lanthanum, neodymium, scandium, yttrium, and ytterbium.

One approach to the problem of determining the source of uranium, vanadium, and other elements in the Sandy mine ore is to compare element variations in the ore (table 13) with elements in unaltered red and altered white sandstone away from ore (table 2). The abundance of vanadium decreases markedly from red to white sandstone; the abundance of uranium decreases from 2 to 1 part per million. If these analyses are correct and if the same results are found for many other samples, the Entrada Sandstone may well be the source of vanadium and uranium in the ores. Other elements show less consistent relationships. Abundances of iron, copper, titanium, silver, lead, and zinc decrease from red to white sandstone, or were detected only in red sandstone. Of these elements, lead and possibly copper and titanium correlate with uranium in the ore, but they are no more abundant in ore than in unaltered red sandstone. Of the elements listed in table 2, only uranium, vanadium, magnesium, chromium, and strontium are more abundant in the ore than in the unaltered red sandstone.

SUMMARY OF MINOR-ELEMENT DATA

The minor elements that seem to be preferentially concentrated in the four uranium deposits for which data are available are listed in table 15. In addition to uranium, elements that are probably or possibly extrinsic in all four deposits are beryllium, cobalt, chromium, copper, lead, vanadium, yttrium, and ytterbium. Of these elements and those that may be extrinsic in one or more deposits, beryllium, calcium, titanium, manganese, boron, gallium, germanium, and lanthanum do not appear in the list of elements that are probably or pos-

TABLE 13.—*Distribution of minor elements relative to uranium, in percent, in Pit 1 deposit, Sandy mine*

[Determined by semiquantitative spectrographic analysis by P. J. Dunton and J. C. Hamilton, except as indicated. 0, looked for but not detected; --, not looked for; Tr., near threshold amount of element; <, less than number shown, but standard sensitivities do not apply]

Laboratory No.	250784	250780	250782	250783	250776	250778	250785	250774	250777	250771	250779
U [1]	<0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.004	0.005
V	.007	.03	.003	.003	.03	.03	.03	.007	.03	.003	.015
Fe	.3	.3	.3	.3	.3	.3	.3	.7	.3	.3	.3
Mg	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
Ti	.07	.03	.03	.03	.03	.03	.03	.07	.03	.07	.03
Mn	.03	.03	.03	.03	.07	.03	.03	.07	.03	.03	.07
B	0	0	0	0	0	0	0	0	0	0	0
Ba	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03
Be	0	0	0	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0
Cr	.0007	.0007	.0003	.0007	.0007	.0007	.0007	.0015	.0007	.0015	.0007
Cu	.0015	.0015	.0015	.0007	.0015	.0015	.0007	.003	.0015	.003	.003
Ga	0	0	0	0	0	0	0	0	0	0	0
Ge	0	0	0	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0	0	0	0	0
Mo	0	0	0	0	0	0	0	.0007	0	.0015	.007
Ni	.0003	.0003	.0003	.0003	.0007	.0003	.0003	.0015	.0003	.0015	.0007
Pb	0	.003	0	0	.0015	Tr.	.0015	0	Tr.	.0015	.0015
Sr	.007	.015	.007	.007	.015	.015	.007	.015	.007	.015	.015
Y	0	0	0	0	0	0	0	0	0	0	0
Yb	0	.00015	0	0	.00015	.00015	.00015	.00015	.00015	0	.00015
Zr	.007	.007	.007	.007	.007	.007	.007	.015	.003	.003	.015

Laboratory No.	250781	250766	238438	250767	250769	250772	250768	250775	238437	250773	238436
U [1]	0.006	0.007	0.008	0.095	0.1	0.28	0.32	0.39	0.62	1.22	1.38
V	.015	.03	.07	[1].112	[1].353	[1].302	[1].23	.03	[1].756	[1].392	[1].498
Fe	.15	.3	.7	.7	.7	.3	.7	.3	1.5	.7	.7
Mg	.3	.15	.7	.7	.7	.7	.3	.3	1.5	.7	.7
Ti	.15	.03	.07	.07	.07	.03	.07	.07	.15	.07	.03
Mn	.03	.03	.07	.03	.03	.07	.03	.03	.07	.03	.07
B	0	0	Tr.	.003	.003	0	0	0	.007	0	.003
Ba	.07	.03	.03	.15	.03	.03	.03	.03	.07	.03	.15
Be	0	0	0	0	.00015	.00015	0	0	.0003	.0003	.00015
Co	0	0	0	0	.003	.003	.003	.003	.003	<.007	.003
Cr	.003	.0007	.003	.0007	.0007	.0007	.0015	.0007	.003	.0015	.0007
Cu	.003	.003	.0015	.003	.0015	.0015	.003	.003	.0015	.003	.003
Ga	0	0	0	0	0	0	0	0	.0015	.0003	.0015
Ge	0	0	0	0	0	0	0	0	<.005	0	<.005
La	0	0	0	0	0	0	0	0	0	.007	Tr.
Mo	0	0	0	0	.0015	0	0	.0015	0	.0015	0
Ni	.0015	.0015	0	.0007	.003	.0015	.003	.003	.0015	.0015	.0007
Pb	0	.007	.003	.003	.015	.015	.007	.003	.07	.015	.07
Sr	.015	.015	.007	.015	.015	.015	.015	.015	.007	.015	.007
Y	0	.0015	0	0	.0015	.003	.0015	.0015	.003	.0015	.003
Yb	.00015	.0003	--------	--------	--------	--------	--------	.00015	--------	--------	--------
Zr	.015	.015	.007	.007	.007	.007	.007	.007	.03	.007	.007

[1] Determined by chemical methods. Analysts: G. S. Erickson, H. H. Lipp, Claude Huffman, E. J. Fennelly, W. D. Goss, D. L. Schafer, and J. S. Wahlberg.

TABLE 14.—*Minor-element content, in percent, of four samples from the Pit I deposit, Sandy mine*

[Semiquantitative spectrographic analyses, by N. M. Conklin and J. C. Hamilton, except as noted. 0, looked for but not detected; <, less than number shown but standard sensitivities do not apply; ----, not looked for; M, major constituent]

Sample No.	Si	Al	Fe	Mg	Ca	Na	K	Ti	Mn	B	Ba	Be	Cd	Ce	Co	Cr
1	----	0.3	1.5	0.07	0.3	----	0	0.3	0.003	0	0.015	0	0	0.3	0.015	0.0007
2	----	3.0	7.0	.7	3.0	----	0	.7	.07	0	.7	0	0	0	0	.015
3	----	7.0	1.5	1.5	1.5	----	7.0	.15	.07	0.03	.15	0.003	0	0	<.01	.0007
4	----	7.0	3.0	1.5	1.5	----	7.0	.07	.07	0	.7	.003	<0.1	0	<.002	.00015

Sample No.	Cu	Dy	Er	Ga	Gd	La	Mo	Nd	Ni	Pb	Sc	Sr	U	V	Y	Yb	Zr
1	0.03	0.03	0.03	0	0.03	0.015	0.015	0.3	0.007	0.15	0.007	0.0007	3.0	0.007	0.15	0.015	0.03
2	.015	0	0	0	0	0	0	0	0	.3	0	.03	M	1.5	.03	0	.07
3	.007	0	0	0.0015	0	0	0	0	.003	.15	0	.007	1.5	1.5	0	0	0
4	.0003	0	0	0	0	0	0	0	0	.07	0	.03	7.0	[1]8.6	.015	----	<.002

[1] Quantitative spectrographic analysis by N. M. Conklin.

DESCRIPTION OF SAMPLES

1. Lab. No. 256493; uraniferous carbonaceous material from small concretion with pyrite; jet black, coaly, specific gravity <2.3.
2. Lab. No. 256496; coffinite concentrate from high-grade ore; trace amounts of quartz, clay, and pyrite as impurities; specific gravity >3.3. Material may contain little or no carbonaceous matter.
3. Lab. No. 256495; vanadiferous clay which gives roscoelitelike X-ray powder pattern; may contain some coffinite as impurity.
4. Lab. No. 279598; same material as sample 3.

sibly extrinsic elements in some deposits, as compiled by Shoemaker, Miesch, Newman, and Riley (1959, table 6). Of the elements in this list, sulfur, phosphorous, selenium, tin, and thallium are not included in table 15, owing to inadequate data. In the Woodrow deposit, however, sulfur is undoubtedly extrinsic. The lack of a distinct correlation between sulfur and iron, uranium, or darkness in Jackpile and Windwhip ores suggests that sulfur (in pyrite) may not be more abundant in ore than in barren sandstone. However, extrinsic sulfur might easily have combined with intrinsic iron.

CARBONACEOUS MATTER AND FOSSIL WOOD

Uraniferous carbonaceous matter that darkens the host sandstone, coats sand grains, and locally impregnates the rock is an abundant epigenetic component of uranium deposits in the Jackpile sandstone. In addition, fossil wood debris, some silicified and some coalified, is present in and near the uranium deposits, and black carbonaceous shale is abundant in the Dakota Sandstone directly overlying the Jackpile sandstone. A knowledge of the origin of these materials, of why some are uraniferous and others are not, and of the chemical and structural nature of the association between uranium and carbonaceous materials is essential to a complete understanding of the uranium deposits. These problems have not been solved, and the data presented must be considered preliminary.

Carbonaceous matter similar to that in the uranium deposits in the Laguna district is common in uranium deposits in many parts of he world. It has been called by various names, including thucholite, asphaltite, uraniferous carbonaceous mineraloid, and carburan. Some of these terms imply a genesis that is far from universally accepted; others have lost their originally intended meaning. The term "thucholite," for example, has been applied to various uraniferous carbonaceous materials that contain no thorium, contrary to the original application (Davidson and Bowie, 1951; Hoekstra and Fuchs, 1960, p. 1717). The carbonaceous matter in the Temple Mountain district, Utah, has been called "uraniferous asphaltite" (Hess, 1922), a term which implies petroliferous origin. More recent literature on that district (Breger and Deul, 1959; Pierce and others, 1958; Kerr and Kelley, 1956), however, shows that the origin of carbonaceous matter there is still controversial. Carbonaceous matter in the ores of the Ambrosia Lake and Laguna districts most closely resembles "nonasphaltic pyrobitumen" in Abraham's classification (1945, v. 1, p. 62), because it is infusible, insoluble in organic solvents, and contains oxygenated bodies. This implies that it is similar to coal, but it does not prove a coaly origin. In view of its uncertain origin, we do not use a genetic term in this report for uraniferous carbonaceous matter.

TABLE 15.—*Minor elements concentrated in ores from the Jackpile, Windwhip, Woodrow, and Sandy deposits*

[C, concentrated; PC, possibly concentrated]

Mine	Fe	Mg	Ca	Ti	Mn	Ag	As	B	Ba	Be	Cd	Co	Cr	Cu	Ga	Ge	La	Mo	Ni	Pb	Sc	Sr	Tl	V	Y	Yb	Zn
Jackpile	----	----	----	----	C	----	----	C	----	C	C	C	PC	C	PC	C	C	----	----	C	----	----	----	C	C	C	----
Windwhip	----	PC	C	PC	C	----	----	----	----	C	PC	C	PC	C	----	PC	----	PC	----	C	----	PC	----	C	C	C	----
Woodrow	C	----	----	----	----	C	C	----	C	PC	----	C	PC	C	PC	----	----	PC	C	C	C	----	C	PC	C	C	PC
Sandy	C	C	----	----	----	----	----	C	C	C	----	C	PC	PC	C	C	C	C	C	C	PC	----	----	C	C	PC	----

We use the general term "carbonaceous matter" (Granger and others, 1961, p. 1195–1196) for all such carbonaceous materials that impregnate, replace, or fill fractures in sandstones and mudstones; are essentially insoluble in acids, alkalis, and organic solvents; and are commonly associated with uranium. All known carbonaceous matter in the Laguna district contains uranium, and available data indicate that it is similar in habit, physical properties, composition, and structure to that of the Ambrosia Lake district (Granger and others, 1961). The term "fossil wood" is reserved for all originally woody material that has been coalified or silicified in place.

FOSSIL WOOD

Silicified logs are locally abundant in the Jackpile sandstone and seem to be most common near the Jackpile and Woodrow mines, where they are confined largely to a zone about 10 feet thick near the middle of the Jackpile. The sandstone in this zone has somewhat more silica cement than the overlying and underlying sandstone and in outcrops tends to stand out as a topographic bench. Individual logs are as much as 3 feet in diameter and 60 feet long. They are knobby, but branches are absent. Though thoroughly silicified, the logs still show woody structure; the silica ranges from light brownish orange to light gray.

Other, sparsely distributed fossil logs in the Jackpile uranium deposit are light gray to black and are strongly mineralized. Such logs are partly silicified and partly coalified. The silica is veined and embayed by uraniferous carbonaceous matter, vanadium clay, and pyrite. Woody structure is well preserved both by silica and by carbonaceous matter, which has a metallic luster. As seen in samples viewed under the reflecting microscope, quartz commonly forms the cell walls, and carbonaceous matter forms the cell centers. Specimens from veinlets of carbonaceous matter can be scratched with difficulty, have a conchoidal fracture and a dull black to submetallic luster, and commonly give an X-ray pattern for coffinite. Coalified wood, particularly that near the margins of logs, is soft and slightly combustible, shows woody structure in polished surfaces, and is less radioactive than the harder material.

One small markedly flattened coalified twig, which apparently was flattened during compaction, was found on the west side of the North ore body. The twig is about 1 inch across and ½ inch thick. It is jet black but does not support combustion, has a vitreous luster and a conchoidal fracture, and gives a coffinite X-ray powder pattern. Viewed in polished section it appears to be made up of a fine intergrowth of two different materials—a relatively soft dull-gray substance, probably a carbonaceous substance, and a relatively hard metallic substance, probably coffinite. Under crossed nicols both materials are weakly to moderately anisotropic and show crosshatch extinction patterns. Small areas of the section show relict cell structure. The metallic substance is most abundant within cells, whereas the duller material is most abundant in the cell walls. The metallic material veins the dull material. The cell structure grades into areas of intergrown metallic and dull materials. Around the margins of the twig, a mixture of both substances impregnates and embays sandstone; this indicates that the twig had some mobility.

The sandstone pipe on the east side of the Jackpile deposit (pl. 6) contains much nonuraniferous coalified fossil wood, especially near its top. Most of this material is about 30 feet above the top of the main Jackpile ore layer. Two bulk samples show 11 and 13 ppm (parts per million) uranium; equivalent uranium determinations give about the same values. The fossil wood ranges from microscopic particles to fragments as much as an inch across. Three physically different types of material are present: jetblack coal that has a conchoidal fracture, brown coal, and a friable substance that looks like charcoal but is similar to low-rank coal (I. A. Breger, written commun., 1958). The brown coal forms fibers and "roots" in small areas of the collapse features. All these materials support combustion.

Infrared spectrograms of the three kinds of coal reveal greater abundances of aliphatic CH and CH_2 groups than do the spectrograms for the uraniferous coals and carbonaceous matter (fig. 24).

BLACK SHALE

Black shale is abundant in beds as much as 2 feet thick at the base of the Dakota Sandstone, and at many levels within the unit. Like the fragmental carbonaceous material in the collapse feature, it is nearly barren of uranium, containing 5 and 6 ppm uranium in 2 bulk samples. The shale is fissile and dark gray and contains sparsely disseminated fine-grained pyrite and small pockets of a white waxy substance. This substance gives a largely aliphatic infrared absorption spectrum that is very similar to that for a resin; the chief difference is that resin lacks the paraffin absorptions between 13.5 and 13.9 microns (fig. 21). The waxy substance may be a resin that was deposited with the coaly black shale.

CARBONACEOUS MATTER

Carbonaceous matter that coats sand grains and locally impregnates sandstone is abundant in the ores of the Jackpile sandstone and may be present in all uranium deposits in the district. It markedly darkens the

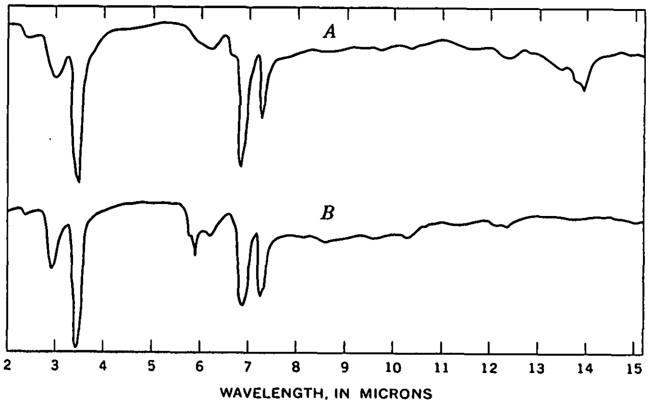


FIGURE 21.—Infrared spectograms. *A*, white waxy substance from black shale in Dakota Sandstone, analyzed by Spectran Laboratories, Denver, Colo. *B*, Parco resin 510, analyzed by Irving A. Breger.

ores, and, as it is uranium bearing, its distribution marks the distribution of the ore. Deposits in the Entrada Sandstone and in the limestone of the Todilto Formation evidently contain far less carbonaceous matter, but in these deposits, too, it may have genetic significance.

DISTRIBUTION, HABITS, AND PROPERTIES

Two suites of shade-graduated samples, totaling 21 samples, from the Jackpile and Windwhip deposits reveal a close correlation between darkness and organic carbon content. Two sequences of 5 samples each were taken vertically across exposed ore near the south end of the North ore body in the Jackpile mine, and 11 samples were obtained in and adjacent to the Windwhip deposit (table 10; fig. 20). The samples were individually crushed and mixed to give homogeneous shades and were then compared with the N–O (white-black) scale in the "Rock-Color Chart". The shade values of this scale range from 1 (black) to 9 (white); the samples, by comparison, ranged from 8 (very light gray) to halfway between 3 (dark gray) and 2 (grayish black). The error of color determination is about one-half of one interval, or 0.5 numerically. Total carbon, mineral carbon, and organic carbon were then determined for all samples (Wayne Mountjoy, analyst). Total carbon was determined by tube-furnace method; mineral carbon, by gasometric method; and organic carbon, by difference.

Visually determined shade values plotted against chemically determined percentage of organic carbon show a close correlation between grayness and carbon (fig. 22). The carbon, having a relatively low specific gravity, occupies a much greater volume per unit weight than any of the other coloring substances (coffinite, uraninite, vanadium micas, and clays) and unquestionably accounts for most of the darkness of the ores. In places, of course, the shade is slightly modified by yellow and brown oxidation products of pyrite, coffinite, and uraninite, but this does not materially affect the relation between shade value and organic carbon.

Organic carbon, possibly the same type, is present in smaller amounts in the Pit I deposit at the Sandy mine. As in the deposits in the Morrison Formation, the unoxidized parts of this deposit in the Entrada Sandstone are various shades of gray, in contrast with the nearly white barren sandstone. The darkness of the low-grade mineralized rock is imparted by vanadium clay, coffinite, and uraninite, as well as carbon, for organic carbon is not abundant. The nearly black shade of high-grade ore is attributable to coffinite and uraninite. These relationships are summarized as follows:

Sample and location		Shade value	Percent			
			U	V_2O_5	Mineral carbon	Organic carbon
A	1 ft above ore	Light gray to very light gray.	0.004	<0.1	2.93	0.06
B	Chips across ore	Medium light gray	.095	.20	.99	.15
C	High-grade ore layer.	Dark gray to black	1.38	.89	1.34	.07
D	1 ft below ore	Very light gray	.003	.001	2.81	.07

The low-grade ore (B) contains slightly less uranium and slightly more vanadium than average Sandy mine ore (table 7). The organic carbon content of this sample (0.15 percent), which is propably typical for average ore, is only about twice that of barren rock a short distance above and below the uranium deposit. The paucity of organic carbon in the high-grade sample suggests that uranium is not as closely associated with carbon as in the ores in the Jackpile sandstone.

In the ores of the Jackpile sandstone, uranium content generally increases with carbon content, but material that contains the most organic carbon does not necessarily contain the most uranium. Ore grade cannot be determined by darkness, although the boundaries of ore closely correspond to the boundaries of zones containing relatively abundant organic carbon. These relationships are summarized in figure 23, in which percentage of uranium is plotted against chemically determined and inferred percentage of organic carbon. Inferred organic carbon content was obtained by converting darkness to organic carbon using data in figure 22. Obviously, the assumption that organic carbon accounts for all of the grayness is not wholly correct; but shade value, in the absence of analytic chemical data, probably gives the best indication of approximate organic carbon content.

Two characteristic habits of carbonaceous matter are distinguishable in typical gray sandstone ore at the Jackpile mine. In ore that contains abundant carbon (as much as 2 percent) but relatively litle uranium (less

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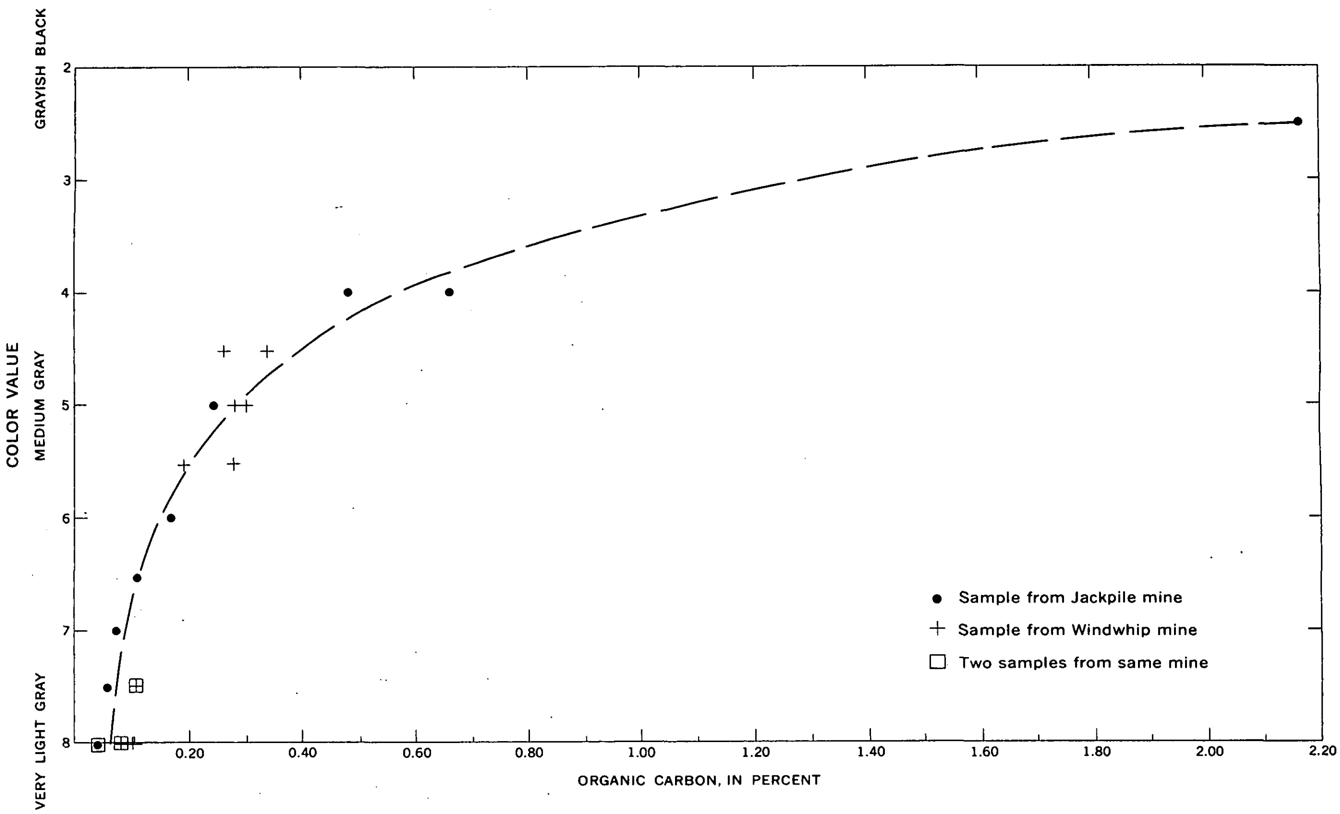


FIGURE 22.—Relation between rock color and percentage of organic carbon for uranium ores in the Jackpile and Windwhip mines. Color values are based on "Rock-Color Chart" (Goddard and others, 1948).

than 0.5 percent), the uraniferous carbonaceous matter is typically uniformly distributed through the sandstone, where it thinly coats each sand grain. It is dull gray and soft. In ore that contains small amounts of carbon (about 0.3 percent or less) and large amounts of uranium (more than 0.75 percent), the uraniferous carbonaceous matter forms aggregates 1–2 millimeters across that solidly cement several sand grains. It is submetallic gray and hard. All gradations exist between these extremes.

At places uraniferous carbonaceous matter also forms veinlets in silicified logs, mammillary coatings on mud galls, and botryoidal masses along the ring fault of the sandstone pipe in the Jackpile mine.

Hardness, specific gravity, and luster (from dull gray to submetallic) appear to increase with increasing uranium content, though quantitative data are not available to verify these relations. The specific gravity of the carbonaceous matter is extremely variable, ranging from much less than 2 (floats in a bromoform-acetone mixture of gravity 2) to more than 3.3 (sinks in methylene iodide); presumably the matter with the highest gravity contains the most uranium. The highly uraniferous carbonaceous matter is much harder than the less uraniferous carbonaceous matter and the nonuraniferous coals. Friedel and Breger (1959) attributed the marked hardening of irradiated coal to an increase in polymeric structure.

Uranium minerals in the massive variety of carbonaceous matter is not homogeneously distributed. Polished surfaces magnified about 1,000 times show blebs of a dull-gray substance, probably carbonaceous matter, embedded in a matrix of a submetallic substance, possibly coffinite or uraninite, or both. At places, areas of blebby texture grade into areas in which the submetallic substance forms anastomosing veinlets in the dull-gray substance. These textures cannot be reasonably interpreted on the basis of available data.

One specimen of uraniferous carbonaceous material collected by Arthur P. Pierce, of the U.S. Geological Survey, from the ring fault gave the following chemical analysis (Clark Microanalytic Laboratories, July 1958):

Component	*Percent*	
	As received	*Ash-free basis*
C	72.00	81.68
H	4.04	4.59
N	.24	.27
Ash	11.86	
	88.14	
O+S (by difference)	11.86	13.46
	≈100.00	≈100.00

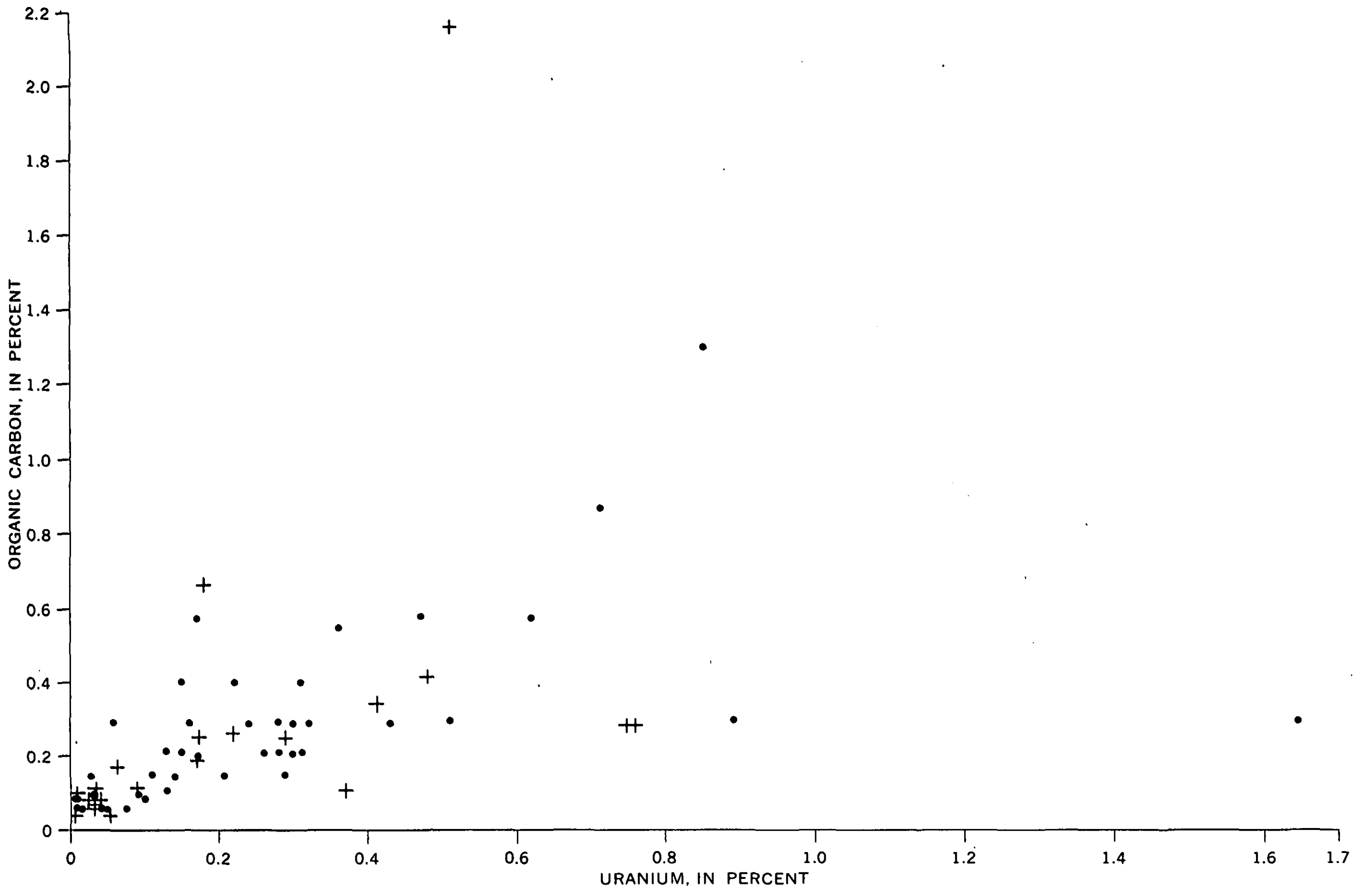


FIGURE 23.—Relation between uranium content and organic-carbon content, Jackpile and Windwhip deposits. Cross indicates chemical analysis of organic carbon by Wayne Mountjoy; dot indicates organic carbon content inferred from rock color.

The sample also contained 3.6 percent uranium as well as a suite of other minor elements (table 9, sample 1).

INFRARED ANALYSIS

Infrared spectrograms of impregnating and botryoidal uraniferous carbonaceous matter from the Jackpile and Woodrow mines are similar to those of fragmental uraniferous and nonuraniferous low-rank coals from the Jackpile mine (fig. 24) and to spectrograms of nonuraniferous coals from other parts of the world (I. A. Breger, written commun., 1960; Friedel and Queiser, 1956; Brown, 1955). These similarities suggest that the same molecular structures exist in all of these physically contrasting types of carbonaceous matter.

All the samples whose infrared spectrograms are shown in figure 24 were prepared by compressing a small amount of the carbonaceous material into 300 milligrams of potassium bromide (I. A. Breger, written commun., 1960). In most samples about 0.7 milligram of carbonaceous material was used, but larger amounts were used in samples H and K. For this and other reasons, the amplitudes of the absorption troughs cannot be compared from one sample to another. Only the positions and relative amplitudes of the absorptions within samples are significant.

Although the relative amplitudes of the largest absorptions shown in figure 24 differ from those of Friedel and Queiser (1956) and Brown (1955), the positions are about the same. One of the most conspicuous absorptions in figure 24 is near 6.2 microns; this absorption is produced at least in part by oxygenated aromatic structure (I. A. Breger, written commun., 1960; Friedel and Queiser, 1956, p. 30). The absorptions near 6.9 and 7.2 microns represent CH_2 and CH_3 groups respectively (Friedel and Queiser, 1956, p. 26). The conspicuous absorption near 3.5 microns in specimens H, I, J, and K (fig. 24) suggests the presence of a resinous substance (I. A. Breger, written commun., 1960; also, compare with fig. 21).

All the curves show a strong absorption at about 2.9 microns. This is attributable to the hydroxyl group, but as both the carbonaceous matter and potassium bromide have adsorbed water which is difficult to remove, it is not known how much of this hydroxyl is struc-

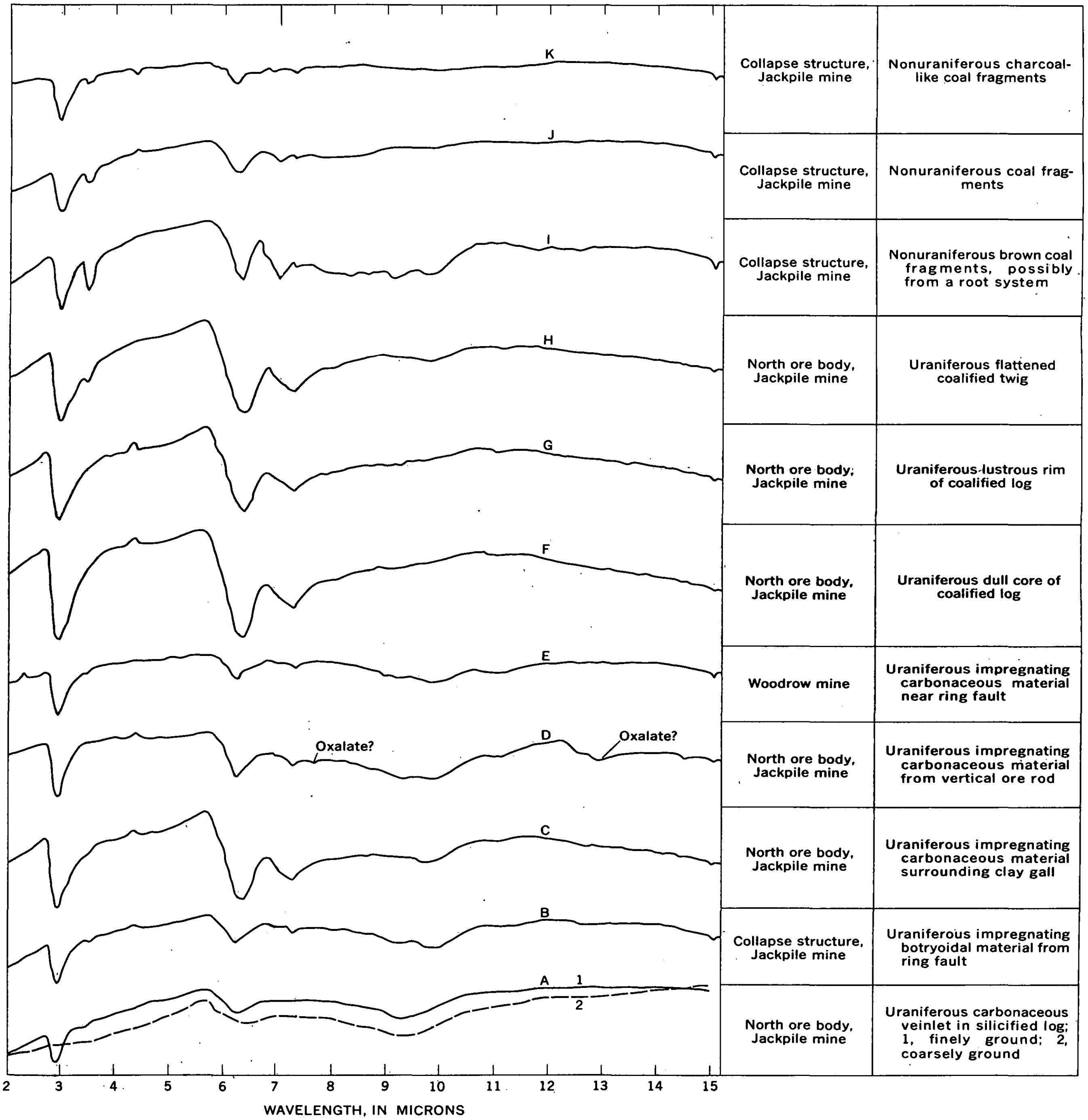


FIGURE 24.—Infrared spectrograms of nonuraniferous coals and uraniferous carbonaceous materials from the Woodrow and Jackpile mines. Sample A collected by Alice F. Corey; infrared spectrogram by Spectran Laboratories, Denver, Colo. All other samples collected by R. H. Moench; infrared spectrograms by Irving A. Breger.

turally combined in the carbonaceous material and how much represents adsorbed water in the sample. (I. A. Breger, written commun., 1960). Possibly the carbonaceous material acquired much atmospheric water in the course of grinding. To test this possibility, Alice F. Corey, of the Atomic Energy Commission, ground and sieved sample A (fig. 24) into three size classes ranging from a fine powder to coarse fragments, and Spectran Laboratories, Denver, Colo., made infrared spectrograms for each size class. The spectrograms of the coarsest and finest ground carbonaceous material are shown in figure 24. The absorption at 2.9 microns is strong for the finest material (curve A1) but absent for the coarsest (curve A2); thus, most of the water in this sample must have been acquired from the atmosphere during grinding. Further, polished surfaces of carbonaceous matter that are exposed to the atmosphere at room temperature and moderate humidity for several weeks may expand and crack their mounts owing to adsorption of water.

An oxalate in the infrared spectrogram of a sample of botryoidal uraniferous carbonaceous matter obtained from the ring fault of the sandstone pipe in the Jackpile mine was tentatively identified by Arthur P. Pierce. The carbonaceous matter is hard and vitreous to submetallic and gives distinct uraninite and faint coffinite X-ray patterns. The major absorptions for the carbonaceous matter are identical with those for calcium oxalate (fig. 25), so the presence of at least the anion oxalate group in the carbonaceous matter is suggested. The cation is unknown. Only small amounts of calcium are present in the sample (table 9, sample 1); iron, lead, or sodium (not determined) are possible cations in the oxalate salt.

Small absorptions in curve D, figure 24, are similar in spacing to those in figure 25.

ORIGIN

The distribution and habits of the carbonaceous matter indicate that it is epigenetic and was introduced in fluid form. This fluid could have been petroleum (Birdseye, 1957; Gruner, 1965a, 1958; Kerr, 1958; Russell, 1958; Zitting and others, 1957; Abdel-Gawad and Kerr, 1961), or it could have been humic acid derived from decaying vegetal matter (Granger and others, 1961). This controversy, which is still unresolved, stems from the fact that the carbonaceous matter has been altered by radioactivity from its original form, so

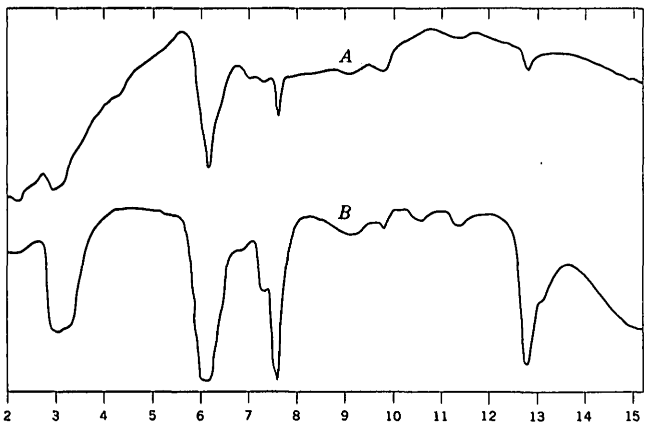


FIGURE 25.—Comparison of infrared absorption spectrograms of botryoidal uraniferous carbonaceous matter from ring fault around collapse feature, Jackpile mine (*A*) and calcium oxalate (*B*). Samples collected by A. P. Pierce; analyzed by Spectran Laboratories, Denver, Colo.

that it is difficult to characterize the original substance. All available data from the Laguna district, combined with the data of Granger, Santos, Dean, and Moore (1961) for the Ambrosia Lake district, favor a humic origin for the carbonaceous matter.

The infrared spectrograms of nonuraniferous and uraniferous coal fragments and of uraniferous carbonaceous matter that impregnates sandstone in the Jackpile and Woodrow mines (fig. 24) indicate that the structures of these diverse substances are closely allied (I. A. Breger, written commun., 1960). Like spectrograms of typical coals (Friedel and Queiser, 1956; Brown, 1955), these spectrograms indicate a dominance of oxygenated aromatic structures over aliphatic structures. In fact, the three nonuraniferous combustible coal specimens apparently contain more petroleumlike aliphatic material than does any of the more controversial carbonaceous matter. Further, the spectrograms of figure 24 differ considerably from those of Pierce, Mytton, and Barnett (1958) for uranium-bearing carbonaceous mineraloids from Panhandle Field, Texas, Eddy County, N. Mex., and the Temple Mountain district, Utah, which evidently formed from organic esters, acids, and other substances related to petroleum.

In spite of inevitable radiochemical damage (Breger, 1948; Charlesby, 1954; Pierce and others, 1958), it is likely that uranium-bearing plant extracts and petroleum-derived materials would be distinguishable by infrared analysis. A possible example of such differences was cited in the previous paragraph. Friedel and Breger (1959) showed that the aromatic and aliphatic constituents of coal are changed proportionately when subjected to radiation; the infrared spectra of irradiated coals are more diffuse than those of nonirradiated coals, but the wavelengths and relative intensities of the absorptions are unchanged. The proportion of aromatic to aliphatic structures is greater in coals than in petroleums (Friedel and Queiser, 1956; Brown, 1955); though these structures will be damaged by radiation, their proportions should remain about the same, and their differences should be distinguishable by infrared analysis. For this reason the similarities of the spectrograms in figure 24 to those of coal, as well as their dissimilarity to those of petroleum, are good evidence for a coal or coal extract origin. Abdel-Gawad and Kerr (1961, fig. 1) showed a somewhat disproportionate decrease in the amplitudes of aliphatic relative to aromatic infrared absorptions when they heated asphalt to 300°C, but they did not report whether this experiment was carried out in the absence of oxygen. If oxygen had been present, their finding could be attributed to differential oxidation of aliphatic and aromatic compounds.

The tentative identification of an oxalate in one and possibly two specimens is further evidence for the plant derivation of the uraniferous carbonaceous matter. Calcium oxalate (the mineral whewellite, $CaC_2O_4 \cdot H_2O$), for example, is a common associate of vegetal remains and coals (Palache and others, 1951, v. 2, p. 1100). Oxalic acid, regardless of what cation it reacts with to form the oxalate salt, is largely of plant origin.

The chemical composition of uraniferous carbonaceous matter from the sandstone pipe in the Jackpile mine, whose low hydrogen content results from radiochemical dehydrogenation, is similar to that of many coalified logs from the Colorado Plateau, and to that of sandstone-type ores in the Ambrosia Lake district, New Mexico, and at Gas Hills, Wyo. (I. A. Breger, written commun., 1959, 1960). These materials are closely allied to coal in composition, which suggests that they are coal or plant extracts.

Petroleum or petroleum residue has not been found in the Jurassic rocks of the district and is not a likely source for the carbonaceous matter unless it has been flushed from other rocks. Although Johnson, MacFarlane, and Breston (1952) showed experimentally that carbonated water can displace petroleum from sandstone, the maximum displacement they obtained left about 5.5 percent petroleum saturation of the pore volume of the sandstone. Different petroleums probably would give somewhat different results, but it is reasonable to infer that if petroleum were present in the rocks of the district, some residue of it should be detectable.

Granger, Santos, Dean, and Moore (1961, p. 1194) concluded that the carbonaceous matter in the Ambrosia Lake ores was probably derived from decaying vegetal matter. They listed three possible sources of water-soluble humic compounds: (1) highly vegetated swamps that covered Morrison sands during deposition of the Dakota Sandstone, (2) streams that transported dissolved humic compounds from vegetated areas in the headwaters during Morrison deposition, and (3) plant debris that was trapped in the Morrison sands. They favored the first-listed possibility.

The three possible sources listed by Granger, Santos, Dean, and Moore (1961) can be applied to the Laguna district as well. Here, black shales representing swampy conditions are abundant in the Dakota Sandstone directly over the Jackpile sandstone, as well as elsewhere; the presence of silicified and coalified plant fossils in the Morrison sandstone suggests that vegetation was locally dense during Morrison deposition; and plant fossils also provide a likely source of humic compounds after burial.

The fact that plant fossils appear to be more abundant in the vicinity of the Jackpile sandstone than elsewhere supports the local "internal source hypothesis" of Granger, Santos, Dean, and Moore (1961, p. 1198). Around the margins of the Jackpile deposit, plant fossils, which include logs as much as 3 feet thick and 60 feet long, are silicified. If silicification of woody material results in the release of soluble humic compounds, or if these compounds are extracted prior to silicification, this debris would provide a ready source of carbonaceous matter. That humic compounds are extractable in alkaline solutions from most woody materials and coals is well known. Further, the fact that Breger (written commun. 1959) was unable to extract humic acid from nonuraniferous low-rank coal from the collapse feature (fig. 24, sample J) by using 5 percent alkali at 100°C indicates that the soluble humic compounds had been preextracted from this sample by natural processes. Alkaline solutions may have permeated the sands and removed the soluble humic compounds from the abundant plant fossils before or during silicification. The dissolved humic compounds could then have been precipitated at the sites of ore deposition by a drop in pH or by an increase in salinity (Vine and others, 1958). Some problems of source, transportation, and precipitation of carbonaceous matter and associated uranium are discussed in the section on origin of uranium deposits (p. 105).

ORE TEXTURES

The relative time the principal components of uranium ores were introduced is a major problem of uranium-ore genesis. Textural relations between the ore minerals and carbonaceous matter in the ores of the Laguna district suggest, but do not prove, that these substances were introduced about contemporaneously.

JACKPILE DEPOSIT

Uraniferous carbonaceous matter is, volumetrically, by far the most abundant introduced component of the Jackpile ores. For this reason, the chief textures of the deposit are those that exist between this material and sulfides, vanadium clay, and the detrital grains and cement of the original sandstone.

Uraniferous carbonaceous matter embays the cementing materials of the host sandstone and detrital silicates; where quartz overgrowths are present, it embays them too. These relations can be seen in typical gray ore and are most obvious in the massive high-grade concentrations of carbonaceous matter. In the massive concentrations, deeply embayed detrital grains are sparsely disseminated in a matrix of solid uraniferous carbonaceous matter. In the specimen shown in figure 26*F*, detrital silicates with authigenic quartz overgrowths are strongly embayed by opaque uraniferous carbonaceous matter. This specimen is from a mass of carbonaceous matter about an inch thick that surrounds a mud gall. The surrounding sandstone is light colored, friable, clay cemented, and unmineralized; authigenic quartz overgrowths surround individual sand grains. Viewed in thin section, the boundary between the unmineralized sandstone and the mass of carbonaceous matter is marked by a thin zone in which the interstitial clays darken toward the carbonaceous matter; thin veinlets of carbonaceous matter follow mineral grain boundaries and small masses fill pores. Inward, the carbonaceous matter becomes more abundant and occupies grain interstices at the expense of clay cement. Within the mass, detrital grains are deeply embayed. Vanadium clay(?) partly surrounds a few quartz grains within the mass. At one place vanadium clay(?) coats a quartz overgrowth which appears to be selectively embayed by uraniferous carbonaceous matter.

Similar replacement textures were observed in many thin and polished sections of moderate- to high-grade ore samples. At places concentrically banded structures outline the replaced detrital grains. Where authigenic quartz overgrowths occur, they are conspicuous in unmineralized sandstone or low-grade ore but are deeply embayed by carbonaceous matter in nearby high-grade ores.

Sharp contacts between high-grade black ore and unmineralized white or very pale orange sandstone are commonly marked by thin light-olive-gray zones less than half an inch thick. They are most conspicuous adjacent to the blackest, most massive parts of nearby vertical ore rods and masses of carbonaceous matter that surround mud galls or line intraformational faults, but similar material also is disseminated through typical gray ore.

Viewed in thin section, the light-olive-gray zones contain light-brown to olive-gray extremely fine grained homogeneous clay that locally fills interstices to the complete exclusion of other substances (fig. 26*C*). The birefringence of the clay is at most rather low; it is variable within the distance between detrital grains, and is generally strongest near the detrital grains. Under crossed nicols the clay exhibits mass extinction that tends to conform to detrital grain boundaries. The variable birefringence and mass extinction appear to be strain phenomena and probably are not characteristics of the mineral species that make up the mass. The refractive indices of the mass are somewhat greater than that of balsam. Optic figures, where obtainable, are negative with a small 2V; such figures are given by aggregates containing innumerable clay particles. X-ray patterns show that the clay is composed of kaolinite and mica, which at places coarsens to discrete flakes of what is probably vanadium clay. The vanadium clay(?) is more birefringent, darker olive gray, and slightly pleochroic.

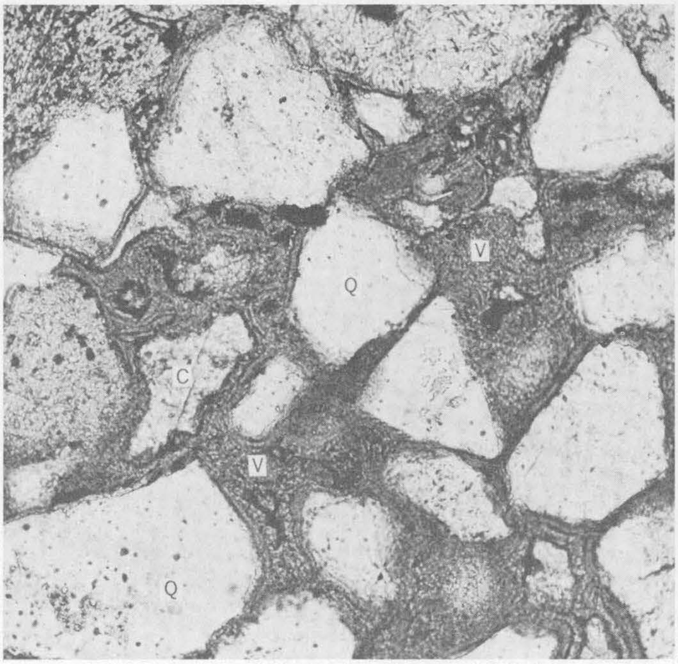
Textures suggest that the olive-gray kaolinite-mica mixtures have replaced kaolinite clots and other fine-grained interstitial materials and have in turn been replaced by uraniferous carbonaceous matter. Colorless kaolinite in unmineralized sandstone may lose its booklike habit toward ore, become darker colored, and blend into massive fine-grained olive-gray clay; or the olive-gray clay may embay clots of coarser kaolinite along boundaries between detrital silicates and the clots. Other fine-grained interstitial materials and detrital grains that appear to have been previously altered to clay also may be engulfed by olive-gray clay.

Along the inner boundary of a light-olive-gray zone, the kaolinite-muscovite mixture commonly grades sharply into opaque black submetallic uraniferous carbonaceous matter (fig. 26*D*). Toward ore the amount of opaque uraniferous carbonaceous matter increases at the expense of the olive-gray clay. At places olive-gray clay is veined by opaque carbonaceous matter.

Where the olive-gray clay is absent, the contacts between opaque uraniferous carbonaceous matter and kaolinite clots are sharp. The carbonaceous matter embays the kaolinite clots along contacts with detrital silicates.

In places the ore has distinct black and white bands. The black bands are rich in uraniferous carbonaceous matter; the white bands, which are generally less than 5 mm thick and follow bedding, intraformational fractures, or sandstone dikes, are rich in kaolinite. Thin sections show that the kaolinite fills pore spaces in fairly continuous layers, and these layers appear to have formed small barriers to the ore-bearing solutions. The textures, similar to those described above, suggest that the kaolinite is older than the carbonaceous matter.

Silicified wood in the Jackpile deposit is black, gray, or brown; and it contains many veinlets and pockets of uraniferous carbonaceous matter, vanadium, clay, pyrite, and barite. Viewed in thin sections, the cell structure is well preserved. The darker shades of gray, observed in hand specimens, are imparted by varying degrees of replacement of silica by black opaque uraniferous carbonaceous matter. The carbonaceous matter invades silica along cell walls and locally replaces large areas of silica. Vermicular trains of vanadium clay line many fractures; associated pyrite occupies fractures and interstices in the vanadium clay. The barite is in relatively coarse plates in fractures. It is com-



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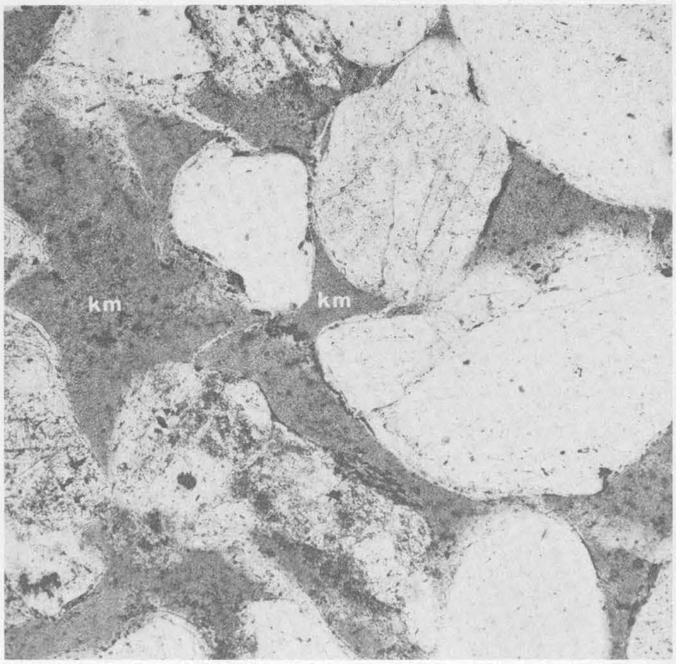

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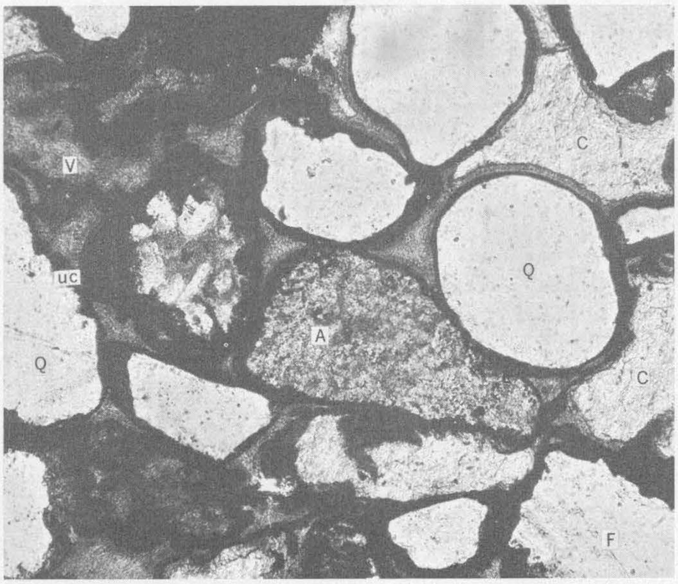
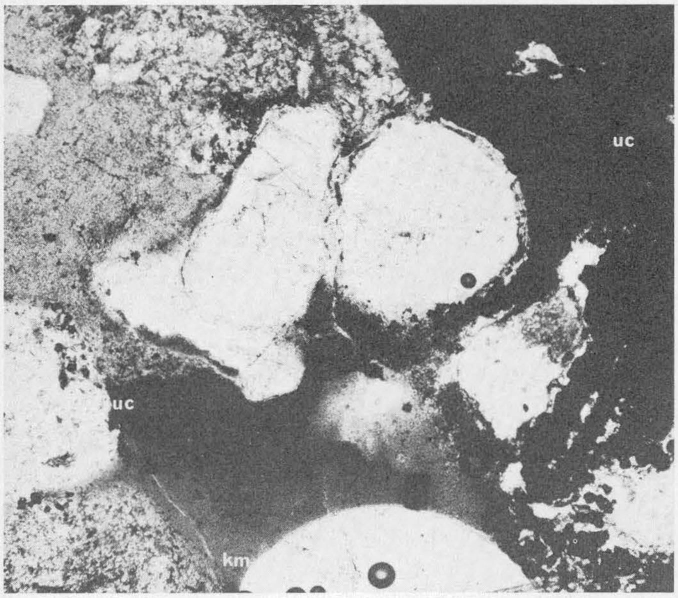


B

FIGURE 26.—Relation of uraniferous material and vanadium clay to host rocks. *A*, Calcite cement (C) and detrital quartz (Q) replaced by vanadium clay (V); Sandy mine. × 130. *B*, High-grade ore, Pit 1 deposit, Sandy mine. uc, opaque uraninite-coffinite mixture; V, vanadium clay; C, calcite; Q, quartz; A, argillized grain; F, feldspar. × 130. *C*, Sandstone cemented by kaolinite-muscovite mixture, km; Jackpile mine. × 80. *D*, Gradation between kaolinite-muscovite mixture, km, and opaque unraniferous carbonaceous matter, uc; Jackpile mine. × 90. *E*, Embayment of detrital silicates by uraniferous carbonaceous matter; Woodrow mine. × 125. *F*, Embayment of detrital silicates by uraniferous carbonaceous matter; Jackpile mine. × 80. *G*, Vanadium clay veinlet (V) in silicified wood; Jackpile mine. × 90. Photographs by Richard B. Taylor.

monly colorless but is yellow near pyrite and uraniferous carbonaceous matter. These textures indicate that the silicified logs have been replaced, but the age relations among the uraniferous carbonaceous matter, vanadium clay, pyrite, and barite are not clear.

A typical veinlet of vermicular vanadium clay in a silicified log is shown in figure 26*G*. The vanadium clay is dark brown, slightly pleochroic to yellowish brown, and strongly birefringent. X-ray patterns are similar to those of roscoelite or muscovite. Handpicked material contained 7 percent each of vanadium, potassium, and aluminum, as determined by semiquantitative spectrographic analysis (Nancy M. Conklin, analyst).



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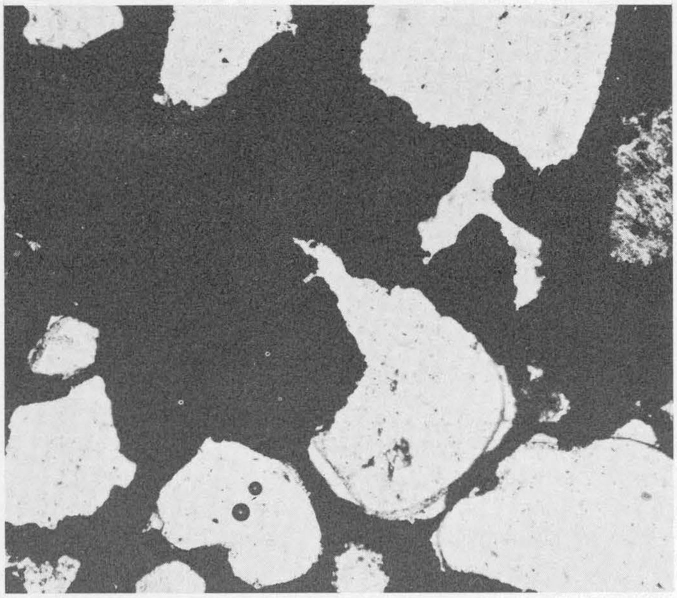

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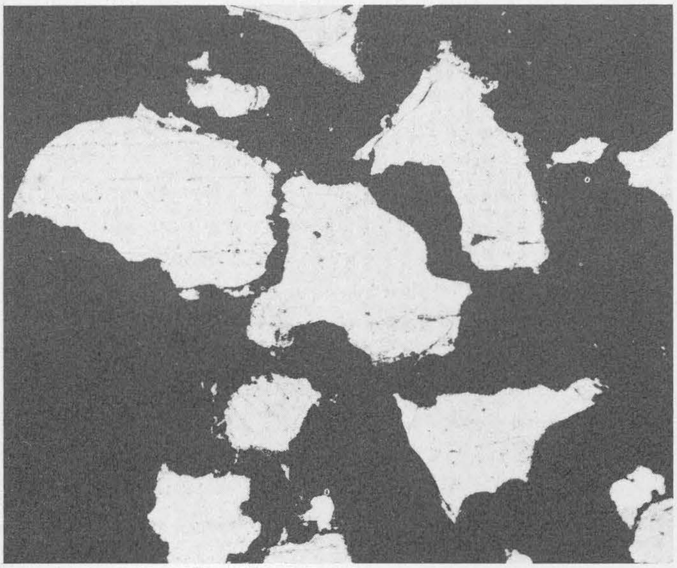

F

G

Pyrite is present in both ore and barren sandstone as disseminated small cubes, but its relative abundance in each is not known. It commonly forms abundant small cubes and irregular masses in gray mudstone in the Jackpile deposit, and it locally is abundant in the gray rim surrounding the red, hematite-rich core of zoned mud galls. Pyrite is also present in high-grade concentrations of uraniferous carbonaceous matter. There it forms small veinlets between carbonaceous matter and detrital grains that have been embayed by the carbonaceous matter, or veins and embays detrital grains and is locally embayed by carbonaceous matter.

Galena has been found as small irregular grains in some of the highest grade concentrations of uraniferous carbonaceous matter.

Barite is sparsely disseminated in parts of the ore. In one specimen of sandstone ore the barite is in small irregular grains that are surrounded by pyrite.

WOODROW DEPOSIT

Woodrow ore is notable for its high grade and abundance of sulfides and for the variety of habits of the minerals it contains. Thus, it also exhibits a variety of ore textures.

As in the Jackpile deposit, excellent replacement textures have been produced where uraniferous carbonaceous matter has replaced original detrital and cementing materials. Where most concentrated, the uraniferous carbonaceous matter occupies interstices, having replaced the original silt and clay, and strongly embays detrital fragments. Where quartz overgrowths on sand grains were originally present, they remain only as relicts that are cut sharply by the uraniferous carbonaceous matter (fig. 26 *E*).

In typical high-grade specimens the uraniferous carbonaceous matter coats grains of pyrite, fills interstices between pyrite grains, and embays pyrite to some extent. Where uraniferous carbonaceous matter is in contact with calcite or dolomite, it commonly embays the carbonates along the cleavages.

At places near the boundary ring fault, sulfide minerals and uraniferous carbonaceous matter form boxwork textures that are governed by the intersections between bedding and fractures. Megascopically, pyrite and marcasite form the intersecting veinlets of the boxwork; microscopic study, however, suggests that the uraniferous carbonaceous matter formed later than the sulfide minerals. Pyrite and marcasite strongly embay the detrital grains; in turn, the uraniferous carbonaceous matter coats the sulfides and embays them slightly along cracks, grain boundaries, and growth lines. Most likely the pyrite and marcasite first invaded the rock, forming intersecting veinlets along bedding planes and fractures. Subsequently, uraniferous carbonaceous matter impregnated and partly replaced the sandstone, and replaced the sulfides to a lesser extent.

Pyrite and marcasite evidently replaced sandstone and mudstone. Although large hand specimens contain more than 90 percent intergrown pyrite and marcasite, relict bedding is obvious; the outlines of the original sand grains can be seen in places. Where the replacement has not gone to completion, pyrite and marcasite fill interstices between sand grains; some grains of detrital quartz and feldspar are crossed by veinlets of the sulfide minerals. The isolated fragments of quartz and feldspar grains are optically continuous and have not been disoriented; thus, the veinlets probably formed by replacement along cleavages and fractures. Pyrite and marcasite appear to have first filled pore space, then replaced the clay cement and altered feldspars, and then invaded the fresh feldspar and quartz. This conclusion is drawn from the observation that as degrees of replacement increase, the remaining detrital grains are progressively fresher; that is, less of the altered material remains.

Chalcopyrite is locally disseminated abundantly in the uraniferous carbonaceous matter and is rarely not associated with this material. Most of the boundaries between chalcopyrite and carbonaceous matter do not show age relations. At places short prongs of chalcopyrite extend into uraniferous carbonaceous matter.

Calcite, dolomite, pyrite, and marcasite fill some of the sparse vugs in the pipe. The dolomite lines the vug walls and penetrates the surrounding mudstone. The calcite, which has good rhombohedral terminations, encrusts the dolomite. Marcasite and pyrite are associated mostly with the dolomite. Marcasite is concretionary, in radiating blades, and appears to have replaced dolomite. At some places pyrite forms the centers of the marcasite concretions; at other places it coats the concretions, apparently replacing dolomite at the boundaries.

A bone fragment about 2 inches in diameter was found in the high-grade part of the ore. The core of the bone consists mainly of fine-grained apatite and sand, whereas the outer part consists dominantly of apatite and has closely spaced concentric partings. The partings are filled with coffinite, pyrite, marcasite, and quartz. Coffinite was determined by X-ray; its distribution along concentric, radial, and irregular fractures was shown by autoradiograph. Viewed in polished section, the coffinite appears to grade sharply into softer dull black apatite; in thin section a sharp gradational color change can be seen between opaque, probably carbon-bearing, coffinite and deep-brown apatite. Quartz veinlets cut coffinite. Pyrite is associated with both coffinite and quartz; its textures and distribution suggest that some pyrite formed contemporaneously with coffinite, some later than coffinite but earlier than quartz, and some contemporaneously with quartz. As seen under oil immersion at high magnification, some coffinite contains finely disseminated pyrite. This fine-grained pyrite is locally sufficiently concentrated to form larger areas of rough-reflecting pyrite. These areas and the coffinite are veined by smooth-surfaced pyrite, probably of the same generation as that which is associated with quartz. Some pyrite in the veinlets is strongly embayed by quartz, but some is so intergrown with quartz that the two appear to have formed simultaneously. Marcasite is associated with the youngest pyrite.

Well-crystallized botryoidal coffinite was found in a small vug in Woodrow ore (Moench, 1962b). The coffinite is associated with pyrite, barite, and small amounts of cobaltite, wurtzite(?), galena, chalcopyrite, and possibly vanadium clay. A mudstone fragment within the vug is partly replaced by fine-grained coffinite that is probably mixed with carbonaceous matter; these materials in turn are cut by anastomosing veinlets of pyrite and cobaltite. The relict mudstone fragment is encrusted with botryoidal coffinite, which contains small contemporaneous concretions of cobaltite and grains of wurtzite(?), chalcopyrite, and galena. In turn, the botryoidal coffinite is encrusted with pyrite, and the pyrite is encrusted with barite. Vanadium clay(?) occupies interstices between the pyrite and barite crusts.

PIT I DEPOSIT, SANDY MINE

The Pit I deposit, in the Entrada Sandstone, is small but is locally high grade and relatively unoxidized. As carbonaceous matter is less abundant and vanadium is more abundant than in deposits in the Jackpile sandstone, textures between vanadium clay and uraninite or coffinite are more readily seen. Uraninite and coffinite in this deposit, however, are not distinguishable except by X-ray. They are assumed to be intimately mixed in various proportions.

As in the Jackpile and Woodrow deposits, replacement textures are conspicuous in the Pit I deposit. High-grade ore characteristically has a mottled appearance. At places the mottling between black ore and light-gray or white relatively unmineralized sandstone resembles graphic intergrowths; the dark areas appear to have invaded the light along bedding planes and in irregular patches between bedding planes. At places the mottling has the appearance of sinuous concentrically banded rods (fig. 27). The significance of this feature is not known.

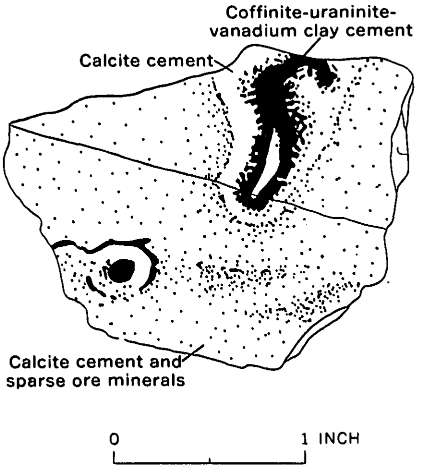

FIGURE 27.—Concentrically banded ore rods in small hand specimen, Pit 1 deposit, Sandy mine.

Microscopic study of mottled textures shows that they are due to vanadium clay and the coffinite-uraninite mixture replacing the cement and detritus of the sandstone. Viewed in thin sections, mixtures of vermicular vanadium clay, coffinite, uraninite, and pyrite completely occupy grain interstices in the dark areas, whereas calcite and subordinate clay cement the sandstone in the light areas. Along boundaries between light and dark areas, vanadium clay lines the contacts between calcite cement and detrital grains; but toward darker areas the vanadium clay increasingly embays and veins calcite and locally fills grain interstices, where "islands" of relict calcite cement remain (fig. 26*A*). At places separate "islands" have the same optical orientation, and locally calcite is veined by vanadium clay along calcite cleavages. In the darkest areas, opaque coffinite-uraninite mixtures coat sand grains and form irregular intergrowths with vanadium clay (fig. 26*B*). Uraninite-coffinite embays sand grains, and intergrowths of vanadium clay and uraninite-coffinite occupy spaces that evidently were once occupied by detrital grains (fig. 26*B*). The argillized grains, probably originally feldspar or rock fragments, are composed of a greenish-brown micaceous substance, probably vanadium clay. The replacement of detrital grains and cement by ore minerals is also illustrated by the modal analyses listed in table 5.

Sulfides, mainly pyrite, are distributed in and around the deposit. Within the deposit pyrite is generally anhedral and particularly associated with vanadium clay. Near the west end of the deposit, several small concretions of pyrite and uraninite are exposed. The concretions are an inch or two across and are flattened parallel to the bedding. Uraninite, which locally has colloform structure, forms the core of the concretions and strongly embays sand grains. Pyrite forms the rim of the concretions and also appears to embay detritus. The central position of the uraninite in the concretions suggests that it formed earlier than the pyrite. Pyrite appears to have formed in two generations, for equidimensional pyrite grains are locally rimmed by additional pyrite.

A trace of galena was found in the highest grade ore. The galena forms minute equidimensional grains associated with vanadium clay and the uraninite-coffinite mixture.

CRACKPOT DEPOSIT

Because the Crackpot deposit had been mined out at the time of this study, the only ore specimens available to us were collected from the mine dump or were given by Lowell S. Hilpert, of the U.S. Geological Survey. These specimens are adequate, however, to show the common textures of the ore minerals in both the bedded and massive limestone units of the Todilto Formation.

Vanadium clay, uraninite, and sparse pyrite are distributed mainly along the silty laminae in the stratified limestone and along irregular silty laminae in the massive limestone unit. At places they also line the walls of carbonate-filled intraformational fractures that probably formed by shrinkage during consolidation of the limestone. In the fractures, where the vanadium clay and associated uraninite form a thin layer separating coarse calcite in the fracture and the fine-grained laminated limestone of the wall, contacts against the coarse calcite are sharp, whereas those against the limestone are gradational. The textures indicate that the vanadium clay and associated uraninite postdated the fractures, but the age relations between the ore minerals and the coarse calcite in the fracture are obscure.

Viewed in thin sections, vanadium clay commonly surrounds small equant grains of pyrite and embays calcite and detrital silt and clay. Uraninite occurs in thin veinlets along the contact between vanadium clay and calcite.

SUMMARY

The study of ore textures clearly indicates that replacement was a major process in uranium ore deposition. Uraniferous carbonaceous matter and pyrite have strongly replaced detrital silicates, quartz overgrowths, and clay cement in the Jackpile and Woodrow deposits. Vanadium clay, pyrite, and the assumed mixture of coffinite and uraninite have replaced detrital silicates and carbonate and clay cement in the Sandy mine. Evidently, vanadium clay, uraninite, and pyrite have replaced calcite and clay- and silt-sized detrital silicates in the Crackpot deposit.

Except in a few specimens, no consistent paragenetic sequence of deposition of ore minerals can be listed from observations made to date. The best evidence for a close temporal relation between coffinite, pyrite, and other sulfides was found in the Woodrow deposit (Moench, 1962b). There, botryoidal coffinite and cobaltite in a vug closely followed or overlapped in time a generation of pyrite and cobaltite, and was followed successively by more pyrite, barite, and still more pyrite. However, the massive pyrite-marcasite replacement deposits in the Woodrow evidently formed before most of the coffinite and the coffinite-bearing carbonaceous matter. The scant vanadium clay(?) in the deposit evidently followed coffinite and at least one postcoffinite generation of pyrite.

In other deposits pyrite evidently both predates and postdates uraniferous carbonaceous matter or the assumed coffinite-uraninite mixtures.

The textural relations between vanadium clay and the other ore minerals do not definitely indicate the age relations between them. Textures seen in figure 26 suggest, but do not prove, that the uraninite-coffinite mixture formed later than vanadium clay.

Textures observed in a mineralized log in the Jackpile deposit suggest that pyrite formed during and after vanadium clay, and before and after uraniferous carbonaceous matter.

SULFUR ISOTOPES

Jensen (1958, 1959) showed that the $S^{32}:S^{34}$ ratio in sulfides from ore deposits of generally accepted hydrothermal origin is remarkably uniform and is close to that of meteoritic troilite, whereas the $S^{32}:S^{34}$ ratio for sulfides in sedimentary rocks and sandstone-type uranium deposits are not uniform and differ considerably from that of meteoritic troilite. Jensen (1958, 1963) attributed the wide spread of $S^{32}:S^{34}$ ratios in sulfides in sandstone-type uranium deposits to fractionation of the sulfur isotopes in the course of reduction of sulfates by anaerobic sulfate-reducing bacteria. He suggested that this biogenic process has a strong bearing on the origin of sandstone-type uranium deposits.

Many sulfide-bearing samples from the Laguna district, most of which were furnished by us, were analyzed by Cyrus W. Field for their sulfur isotope ratios. Of 38 samples, 20 were from the Woodrow mine, 9 were from the Jackpile mine (7 from black shale of the Dakota Sandstone and 2 from ore), 3 were from the Saint Anthony mine, 4 were from the Sandy mine, and 1 each were from pyrite concretions in the Bluff and Gallup Sandstones. The results of the analyses were published by Jensen, Field, and Nakai (1960) and by Jensen (1963).

The most striking feature of Field's data for the Laguna district is the great range of isotope ratios in the sulfides (Jensen and others, 1960, p. 195). The $S^{32}:S^{34}$ ratios in the Jackpile and the Saint Anthony deposits vary 2.2 and 5.7 percent, respectively; some samples are enriched in S^{32}, and others in S^{34}. Ratios in the Woodrow deposit vary 6.1 percent, the greatest variation noted by Field or previous workers within a single deposit; of 20 samples, all but 3 are enriched in S^{34}. This variation undoubtedly reflects in part the large number of samples obtained from the Woodrow mine. Sulfur in pyrite from black shale in the Dakota Sandstone is enriched in S^{32}. All analyzed samples from the Sandy mine are enriched in S^{32}; these samples include two from unmineralized limestone, one from a pyrite-uraninite concretion, and one, of pyrrhotite, from a metamorphosed uranium deposit in limestone. The pyrrhotite probably formed at the expense of pyrite during metamorphism. The two samples of pyrite from the Bluff and Gallup Sandstones show less variation from standard troilite than do sulfides from the uranium deposits.

The unusually great enrichment of the heavy isotope in Woodrow sulfides is difficult to explain, for many samples show greater S^{34} enrichment than is common in sulfates. This means that if the sulfides formed by bacterial reduction of sulfate, some of the sulfate must have been exceedingly enriched in S^{34}. Field (in Jensen and others, 1960, p. 196–205) suggested that the S^{34} enrichment resulted from bacterial reduction of a finite quantity of sulfate, which perhaps traveled up the Woodrow pipe from the gypsum of the Todilto Formation. As bacterial action continued to generate S^{32}-rich hydrogen sulfide, which escaped, the remaining sulfate became increasingly enriched in S^{34}. This source of sulfate is unlikely, because the Woodrow pipe probably does not extend below the base of the Morrison Formation.

Although some sulfur isotope data for the district are difficult to interpret, at least the wide range of ratios is in marked contrast to the small range of ratios in sulfides from some "magmatic hydrothermal" deposits (Jensen, 1959). This difference suggests at least that the sulfides associated with the uranium deposits of the Laguna district have had a more complicated history; either they were not derived directly from a common source, or the sulfur isotopes were fractionated by bacterial action, or both.

DESCRIPTION OF URANIUM DEPOSITS

In 1960 only two deposits in the Laguna district—the Jackpile and Saint Anthony deposits—were being mined. The Paguate deposit is among the several other large deposits that had been blocked out by drilling. Many small deposits had been prospected and partly or completely mined out before 1956. Those that were mined, prospected, or found prior to 1956 are described in the following pages. Deposits in the Morrison Formation are described first, then those in the Entrada Sandstone and the Todilto Formation.

JACKPILE MINE

The Jackpile mine, an open-pit operation owned by the Anaconda Co., is one of the world's greatest producers of uranium. It is in the central part of the Laguna district (pl. 3), about 7½ miles north of Laguna, and is easily reached by gravel road.

The Jackpile deposit was discovered on November 8, 1951, by aerial radiometric reconnaissance by Woodrow Bird House and Dale Terry. Examination and sampling of the outcrop on the south side of a low mesa, by House, Terry, and J. B. Knaebel on the following day revealed a uranium deposit with an exposed length of about 100 feet, an average thickness of 8½ feet, and an average grade of 0.91 percent U_3O_8. The first work was done on the outcrop in December 1951 (Lowell S. Hilpert, written commun., Nov. 16, 1959).

Subsequent drilling on the south end of the mesa proved a deposit of moderate size, now known as the South ore body. In 1953, drilling in the central part of the mesa, a short distance to the north, outlined a much larger deposit, now called the North ore body. Active mining began in 1952, and full production—about 3,000 tons of ore per day—was achieved in 1956. A spur railroad line was extended north from Laguna, and over this line the ore is shipped to Anaconda's mill at Bluewater, N. Mex. By 1958 more than 3 million tons of uranium ore had been shipped; and by 1963 about 6.5 million tons of ore, including some from the Paguate deposit, had been shipped. This ore yielded about 28 million pounds of U_3O_8 (Kittel, 1963, p. 167).

According to production and assay data, the first 3 million tons of ore shipped from the mine averaged 0.23 percent U_3O_8 and 0.13 percent V_2O_5 (table 6); the total production to 1963 averaged slightly less than 2.2 percent U_3O_8. The calcium carbonate content of the ore is low, averaging 0.8 percent in 2.3 million tons.

DIMENSIONS AND CHARACTER OF DEPOSIT

The deposit is in an area where the Dakota Sandstone dips about 1° N. into the San Juan Basin. In the area of the open pit, the Dakota Sandstone strikes N. 60°–90° E. and ranges in dip from horizontal to about 2° N. The deposit is semitabular and is roughly conformable to the strata.

The dimensions and form of the Jackpile deposit are shown on plate 6B, a fence diagram prepared largely from Anaconda Co. drill-hole data. The South ore body is shown along section *A–A′*; the North ore body generally comprises the ore shown in the rest of the fence diagram. Actually the North and South ore bodies are connected by a weakly mineralized zone, and the separation is arbitrary. The ore bodies consist of many overlapping layers which aggregate over 6,000 feet in length and about 1,200–3,000 feet in width and have an average combined thickness of about 20 feet. Section *H–H′* (pl. 6B) follows the approximate center of the thickest part of the ore; along this line, single ore layers locally exceed 60 feet in thickness, and the total thickness of ore locally approaches 100 feet.

The ore is outlined on plate 6B with varying degrees of confidence. At the south end of the area shown, section *C–C′* and southward, drill holes are close spaced—in many places on 50-foot centers or closer. This part of the deposit was being worked at the time of this study (1956), and ore distribution is shown accurately. Northward from section *C–C′*, drill holes are wider spaced, mostly on 100- or 200-foot centers, and the ore distribution is more interpretive. In this area ore layers were projected between drill holes where they closely conform to the stratigraphic layering or show a consistent rise or fall between several holes. Here the general distribution is assumed to be as shown, but further drilling and mining undoubtedly will change the picture somewhat.

The Jackpile deposit may be characterized as several ore layers that in part overlap successively and in part split and diverage to the north and northwest. Only locally do individual layers not conform with the north-northwesterly dip of the Dakota Sandstone, but the crude overlapping tends to place the uppermost layers successively higher in the Jackpile sandstone toward the north-northwest (pl. 6 B). The high layer shown along the west side of section *F–F′* and near the west end of section *E–E′* is called the Windwhip horizon by Anaconda Co. geologists, because the Windwhip deposit is at the same elevation a short distance west of "*E*" on section *E–E′*. Northward from the intersection of sections *F–F′* and *H–H′*, the North ore body appears to break up into many discontinuous layers that are distributed through the full thickness of the Jackpile sandstone.

The lowermost ore may follow the base of the Jackpile sandstone, as is suggested in parts of most sections on plate 6B; locally ore appears to extend below the base of the sandstone, particularly in parts of *D–D′* and near the east side of *C–C′*. Some ore may erroneously be shown below the base of the Jackpile sandstone, because in many places the contact is necessarily placed arbitrarily. The deepest that ore has been found below the base of the Jackpile sandstone is in a single drill hole near the east end of section *D–D′*.

The uppermost ore locally follows the base of the Dakota Sandstone, as in section *B–B′* and in a few places near the north end of the deposit. None of these occurrences were exposed in mine workings at the time of this study.

Plate 6C provides a comparison between the distribution of ore exposed in a wall of the mine and the distribution of ore determined from drill-hole data, shown on plate 6B. Plate 6C is much reduced from the scale of 1 inch: 5 feet at which it was sketched in the field, but it shows the general distribution of the ore in an incomplete cross section through the south end of the North ore body. The ore was sketched on the basis of darkness of sandstone, which shows the concentration of organic carbon but is roughly indicative of uranium content as well (figs. 22, 23).

As can be seen from plate 6C, the upper boundary of ore in most places is sharp, generally continuous, and gently undulant. In contrast, the lower boundary, where exposed, is poorly defined and mostly gradational and is not marked by any specific surface. Unfortunately, in much of the area shown on plate 6C the base of ore is not exposed, and drill-hole data reveal little about the character of the ore boundaries in other parts of the deposit. The ore feathers out at its edges, but thin wisps and rods of ore are found at about the same elevation as the main deposit but several tens of feet thick outside of it.

Within the deposit the ore assumes a nearly infinite variety of forms, some of which are controlled by sedimentary structures or intraformational fractures, but others of which appear to be independent of host-rock structures. The apparently independent forms include ore rolls that are similar in many respects to rolls that have been studied in other parts of the Colorado Plateau, semispherical forms, nearly vertical ore rods, and a multitiude of nondescript forms.

ORE ROLLS

Many rolls, or boundaries of large masses of ore that cut arcuately across sedimentary structures, can be seen on plate 6C. In places the roll boundaries are sharp; more typically they are gradational and lack distinct banding. In places mirror images of rolls are exposed, as at the top of the ore near the center of plate 6C.

Data on the orientation of the axes of rolls are scant. Ore extends unusually deep into the Brushy Basin Member near the east end of section *C–C′* (pl. 6B), on section *H–H′* about halfway between sections *C–C′* and *D–D′*, and on section *D–D′* about halfway between sections *G–G′* and *H–H′*. These three downward extensions may represent a single east-southeast-trending roll. If so, the roll axis is about parallel to the dominant cross-bedding dip direction as determined along the line of plate 6C, and it is parallel to the local Jackpile sandstone isopachs (pl. 6A). In contrast, the inferred roll is oriented at a wide angle to the north-northwest orientation of the North ore body.

ORE RODS

Ore rods, or nearly vertical cylindrical to conical masses of uraniferous carbonaceous matter (fig. 33A), are common in the Jackpile deposit. They are widely distributed in the lower grade parts of the deposit (pl. 6C), particularly in the low-grade zones that separate large ore layers. A few rods, as near the southwest side of plate 6C, appear to be isolated from large bodies of ore. The rods range from less than half an inch in diameter and a few inches in height to as much as 5 inches in diameter and 4 feet in height. Rods typically widen downward, though a few remain about constant in width. The apex of a large rod may be a fraction of an inch in diameter and may be composed of massive uraniferous carbonaceous matter that impregnates the sandstone and, in thin sections, strongly embays the sand grains; downward such a rod gradually widens, and the carbonaceous matter becomes more diffuse. Rarely, a conical rod may be as wide at its base as it is high. (See fig. 33*B*, Saint Anthony mine.) Though the upper end of a rod is typically independent of any recognized sedimentary structure, a few rods extend downward from ore-bearing bedding planes. A rod may grade downward into a large mass of gray ore, or it may bottom in light-colored unmineralized sandstone. Some rods are surrounded by halos of fine-grained olive-gray clay composed of mixed kaolinite and mica.

The composition, the downward widening and dispersion, and the nearly vertical orientation of the rods suggest that they formed by downward flow of an organic fluid. Conceivably, carbonaceous matter was originally precipitated from ground water in small semifluid or jellylike concretionary masses of humic acid. This substance then flowed downward under gravity, and as it flowed it tended to be dispersed by the sandstone. If it flowed downward, it must have been denser than the surrounding pore fluid. A high relative specific gravity may be attributable to a high uranium content and to ash in the carbonaceous matter. If so, the surrounding pore fluid must have been nearly stagnant; otherwise the rods would be inclined in the direction of flow. It is also possible that the carbonaceous matter was precipitated a short distance below a water table, which then dropped temporarily, permitting the carbonaceous matter to flow downward or to be dissolved and reprecipitated by downward-moving water.

If the ore rods were vertical when formed, detailed measurements of their bearing and plunge should indicate whether or not they have been tilted. One rod that was sufficiently large, well defined, and accessible for a detailed measurement was excavated to a depth of more than 3½ feet. A plumb bob was hung from the apex to the approximate center of the base so that the line and rod were alined in the same vertical plane. This plane is approximately parallel to the dip direction of the Dakota Sandstone and defines the bearing of the rod. The angle between the rod and the line in this plane defines the plunge of the rod. These detailed measurements, and the dip of the Dakota Sandstone directly above, determined by planetable mapping, are shown in figure 28. The centerline of the rod could be measured accurately only in the upper 18 inches. Here the rod plunges 88°–88½° S. 15° E., almost exactly normal to the strike and dip of the Dakota Sandstone. At greater depth the plunge of the rod apparently flattens to about 86½°, but the margin of error in determining plunge is considerably greater at depth because the rod becomes less well defined. Photographs of this rod have been published (Moench, 1963a, fig. 5*A*, *B*).

These measurements suggest that the Jackpile deposit has been tilted, but many more measurements are necessary to confirm this theory.

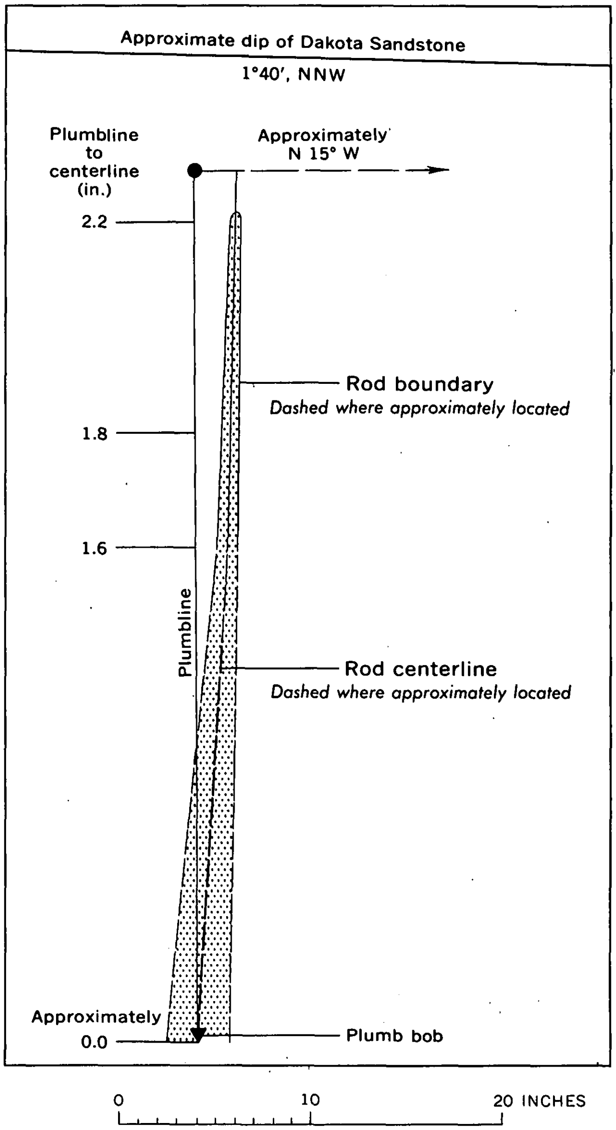

FIGURE 28.—Sketch of excavated ore rod, Jackpile mine, showing downward convergence with plumbline (after Moench, 1963a).

LOCALIZATION BY MINOR STRUCTURAL FEATURES

Although bedding features are commonly cut at various angles by ore boundaries, any feature that was present prior to mineralization may have had a localizing effect on ore deposition. Concentrations of uraniferous carbonaceous matter within trough-shaped sets of crossbeds, along single bedding planes, above or below mudstone beds, and around mudstone galls are common features of the Jackpile deposit. Examples of some of these relationships can be seen on plate 6C. The top of parts of the Jackpile deposit cut horizontally across inclined bedding planes (Hilpert and Moench, 1960, fig. 10), but within the deposit ore is partly localized along bedding planes.

A few small fractures that formed during sedimentation also have localized deposition of uraniferous carbonaceous matter (fig. 29). Most such fractures in the Jackpile mine strike N. 5°–25° E. and dip 50°–80° E. or W. Uraniferous carbonaceous matter is localized along the left side of two small fractures shown in figure 29. The fracture shown in the left side of figure 29 is a small normal fault. The lower part of the fracture shown just left of center in figure 29 is a high-angle thrust fault that deforms the lower part, but not the top, of the thin mudstone bed; this fracture extends upward as a joint and joins a normal fault, which, upward, is truncated by cross-stratified sandstone and, downward, becomes a thin sandstone dike. All these fractures evidently formed by slumping that accompanied Jackpile sedimentation.

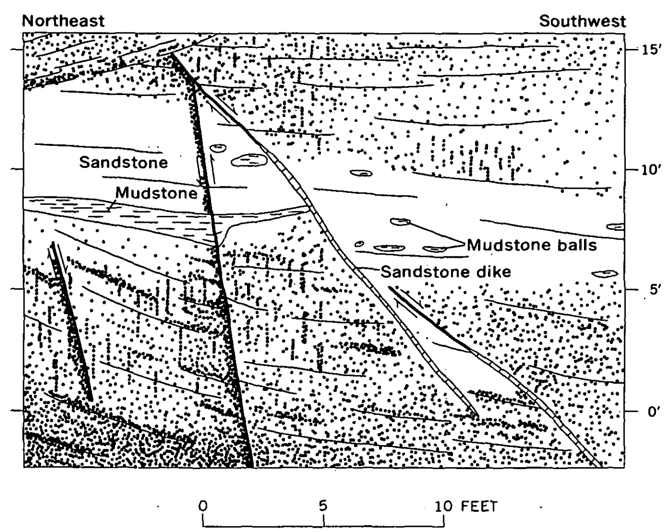

FIGURE 29.—Sketch showing distribution of uraniferous carbonaceous matter along penecontemporaneous fractures, North ore body, Jackpile mine. Density of dots indicates degree of ore concentration (after Moench, 1963a).

RELATION OF DEPOSIT TO SEDIMENTARY TRENDS AND JURASSIC FOLDS

The Jackpile deposit appears to be more closely related to a set of broad Jurassic folds than to sedimentary trends in the Jackpile sandstone. As shown on plate 6A, the long dimension of the deposit is about parallel to the inferred north-northwest-trending folds in the mine area but not to a west-northwest-trending channel inferred on the basis of isopach trends and the average dip direction of crossbedding in part of the mine.

Isopachs of the Jackpile sandstone exhibit two dominant trends in the mine area (pl. 6A)—north-northwest and west-northwest. These two trends are interpreted to reflect the intersection between a west-northwest-trending channel and a set of Jurassic folds that trends north-northeast. The channel and the synclines probably account for local thickening of the Jackpile, and the anticlines probably account for the areas of thin Jackpile. In 1958 the major anticline shown was exposed in the open pit, as then developed, in the general area of section *E–E′* (pl. 6A). At that time the anticline was defined by two thin discontinuous mudstone beds that arched gently over the deposit and converged with the base of the Dakota. The total relief of the beds in the open pit was about 20 feet, but this is a minimum figure for the whole structure because the fold limbs probably extended beyond the limits of the pit. The exact trend of the anticline could not be determined from its exposure in the open pit, but it is probably parallel to a set of north-northwest-trending Jurassic folds that are well exposed about 2 miles southwest of the pit (pl. 3). In the mine area the Jackpile sandstone isopachs north of section *E–E′* (pl. 6A) have a marked north-northwest grain and very likely define the Jurassic anticline that was exposed in the pit in 1958. The marked west-northwest-trending trough, or thickening of the Jackpile, probably represents a paleochannel, because it is about parallel to the average dip direction of crossbedding in the same local area (pl. 6A).

SANDSTONE PIPE

A large cylindrical subsidence structure, or sandstone pipe, is exposed on the east side of the North ore body (pl. 6B). Figure 30 is a detailed map of the wall in which the top of the pipe is exposed. Original stripping operations exposed the upper 25 feet of the pipe in a wall that nearly bisected it; later mining exposed the lower part shown in figure 30 but removed the upper part; still later mining exposed a part of the pipe that is below the level shown in figure 30. Horizontal drilling from a lower bench confirmed the cylindrical shape of the structure.

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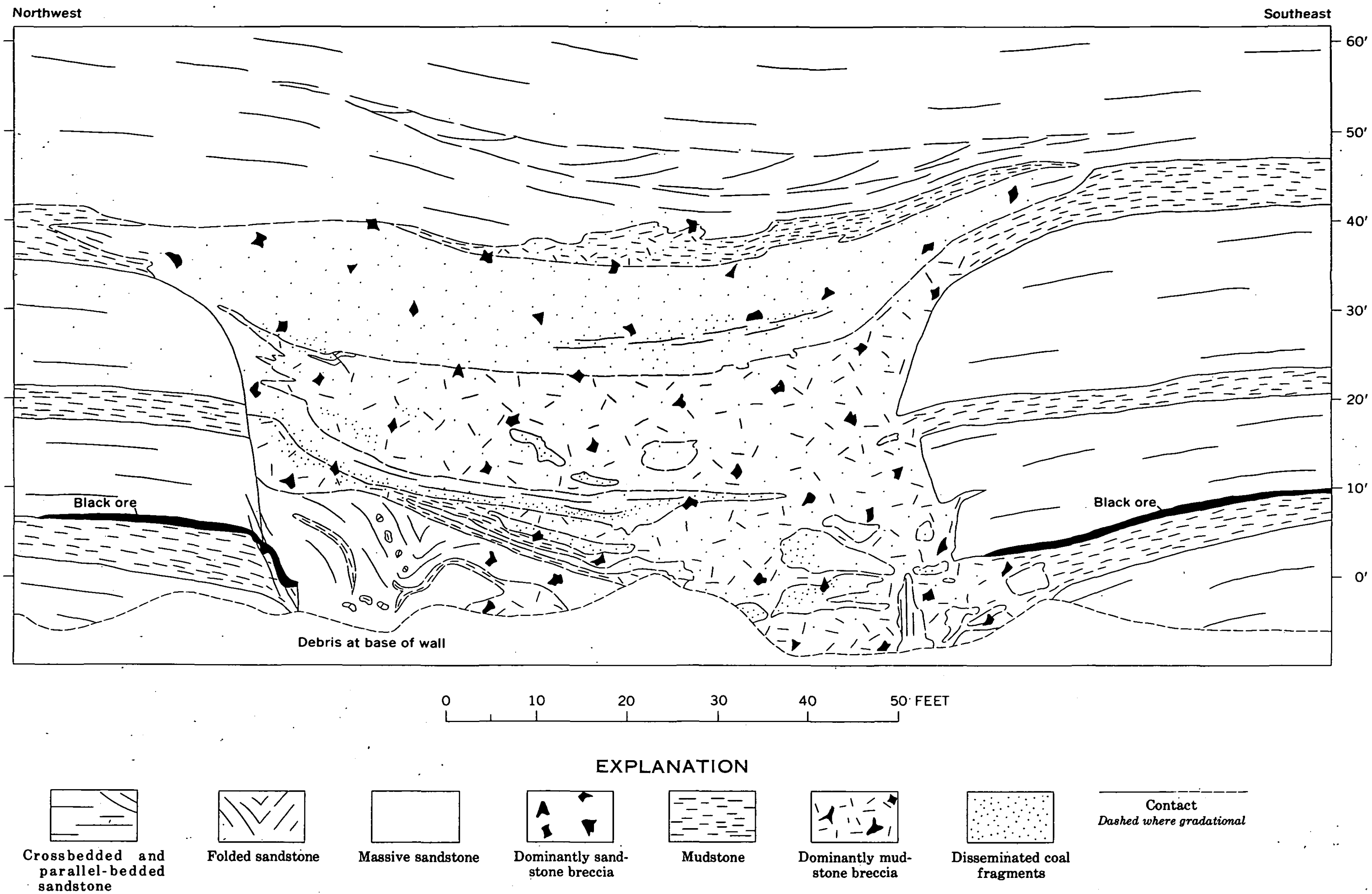

FIGURE 30.—Upper part of sandstone pipe, Jackpile mine. Location of sketch shown on plate 6.

The pipe is composed largely of sandstone fragments embedded in a sandy mudstone matrix. Although the mixture is described as breccia in figure 30 (for want of a better term) the fragments are rounded and many have poorly defined borders. The mixture is compact and without voids and in places appears to have been folded or to have flowed as an unconsolidated mass. The boundary of the pipe is marked by one or more ring faults, or by the broken edges of strata outside the pipe. Gross units, dominantly of sandstone or mudstone, can be mapped, but they cannot be correlated with units outside the pipe. The sandstone and mudstone beds near the pipe sag inward, and strata directly overlying the pipe sag slightly. A single cross-stratified sandstone lens directly over the pipe occupies a shallow depression and appears to represent the last stage in the formation of the pipe, for it is overlain by undeformed sandstone. A thin sill cuts across the pipe below the level shown in figure 30. Superficially, the sill looks as though it has been displaced downward by the pipe; close inspection shows, however, that the sill is continuous across the pipe, and reveals no evidence that the sill has been broken or otherwise deformed by the pipe.

The pipe contains abundant fragmental and virtually nonuraniferous low-rank coal, some of which is so finely divided that it colors the sandstone and mudstone gray. Larger fragments of brown coal, jet-black coal, and charcoal-like material are also present and have been described in the section on fossil wood.

By 1963 a large mass of ore had been extracted from the pipe below the level shown in figure 30. According to Ernest T. Wylie (geologist for the Anaconda Co., oral commun., 1963), the mass was high grade but contained much less sulfide than did the ore from the Woodrow pipe. Wylie reported that the ore body was a crescent-shaped mass (plan view) that bordered the west side of the pipe and extended several feet into the Jackpile sandstone outside the pipe. Uraniferous carbonaceous matter forms botryoidal masses along a fault; on both sides of the fault similar material impregnates sandstone in a thin zone directly on top of a mudstone bed.

CENOZOIC STRUCTURAL FEATURES

In the vicinity of the Jackpile mine, the 100-foot contours drawn on the base of the Dakota Sandstone (pl. 4) indicate a northward dip of about 1°. Planetable mapping of a thin but widespread stratum of black shale indicates that the Dakota strikes N. 60°–90° E. and dips 2° N. in the northern part of the pit and ½° N. in the southern part. The base of the Dakota is not a reliable marker for detailed work because it locally channels deeply into the Jackpile sandstone.

Joints measured in the Dakota Sandstone and in the Jackpile sandstone are entirely consistent with the regional fracture pattern (fig. 14).

Neither the northward tilt nor the Cenozoic joints exhibit any controlling influence on the Jackpile deposit. Recognized structural terraces are neither sufficiently large nor correctly placed to have localized ore by any known process. Although one joint set is about parallel to the long dimension of the Jackpile, the other sets show no relation to the deposits; and joints of all sets cut ore. At places joints contain minerals of high-valent uranium and vanadium that apparently formed during recent oxidation and redistribution.

RELATION OF DEPOSIT TO DIABASE

During the early stages of mining operations many geologists pointed to the discovery of a diabasic sill in the South ore body as evidence of a relation between uranium deposits and igneous rocks. Further mining development and study of the deposit have shown that the diabase, which is of late Tertiary age, intruded a preexisting uranium deposit. In the south end of the open pit, sills cut various parts of the South and North ore bodies. Though nearly concordant, they cross bedding planes along preexisting joints or on irregular surfaces (pl. 6C), and in places the sills rise several tens of feet above the ore bodies. Toward the north end of the open pit, the sills rise stratigraphically well above the ore body and pass into the Dakota Sandstone. In places diabase sills even displace parts of the ore bodies, further demonstrating their younger age (Moench, 1963a, fig. 3).

Diabase sills in the Jackpile mine contain far more uranium than do sills that are well away from known uranium deposits, and uranium tends to be most abundant in the chilled borders of sills that are in direct contact with ore (table 16). In one specimen from a chilled border of a sill (fig. 31), uranophane is distributed along primary joints that parallel the contact of the sill. In another sample, fine-grained uranophane and other, unidentified minerals of hexavalent uranium are disseminated in the dense matrix and are distributed along phenocryst boundaries and joints. These relations suggest that the diabase acquired uranium from the deposits during or after emplacement of the sills.

The metamorphic effects adjacent to the diabase are not great, but some local alteration is related to the diabase. The contacts of the sills commonly are bordered by a thin film of gypsum; and as far as 3 feet above or below the sills, poikiloblasts of gypsum as large as 5 mm

TABLE 16.—*Uranium content of diabase sills and dikes in and near Jackpile mine*

[Analysts: C. G. Angelo, E. J. Fennelly, and H. H. Lipp]

Laboratory No.	Part of sill or dike	Thickness (feet)	eU (percent)	U (percent)	Remarks
254978	Center	0.6	0.023	0.022	Center and chilled borders intensely altered to clay; cuts low-grade ore.
254979	Lower chilled border	.3	.074	.033	
254982	Upper chilled border	.15	.073	.050	Sill cuts moderate-grade ore.
254980	Center	1.2	.037	.063	
254981	Lower chilled border	.2	.11	.23	
254986	Chilled border	.3	.15	.20	Sill cuts high-grade ore.
254987	Center	2.2	.065	.11	
254991	Upper chilled border	.3	.038	.045	Bottom of sill is 3 ft above high-grade ore.
254992	Center	2.4	.046	.065	
254989	Upper chilled border	.3	.008	.008	Sill cuts "barren" sandstone 20 ft above ore.
254988	Center	3.7	.001	.0016	
254990	Lower chilled border	.3	.003	.003	
254984	Center	3.0	.001	.0006	Cuts "barren" sandstone 30 ft west of North ore body.
254985	Chilled border	.3	.054	.055	
259983	Whole sill	.9	.010	.009	Cuts "barren" sandstone 150 ft east of North ore body.
256203	Center	3.0	<.001	.0001	Diabasic dike exposed 5,000 ft east of Jackpile mine and 1,000 ft north of Woodrow mine.
256204	Chilled border	.3	<.001	.0001	

in diameter are disseminated throughout the ore. Calcite poikiloblasts are also common in the same zones, and in places the rocks are largely calcite cemented.

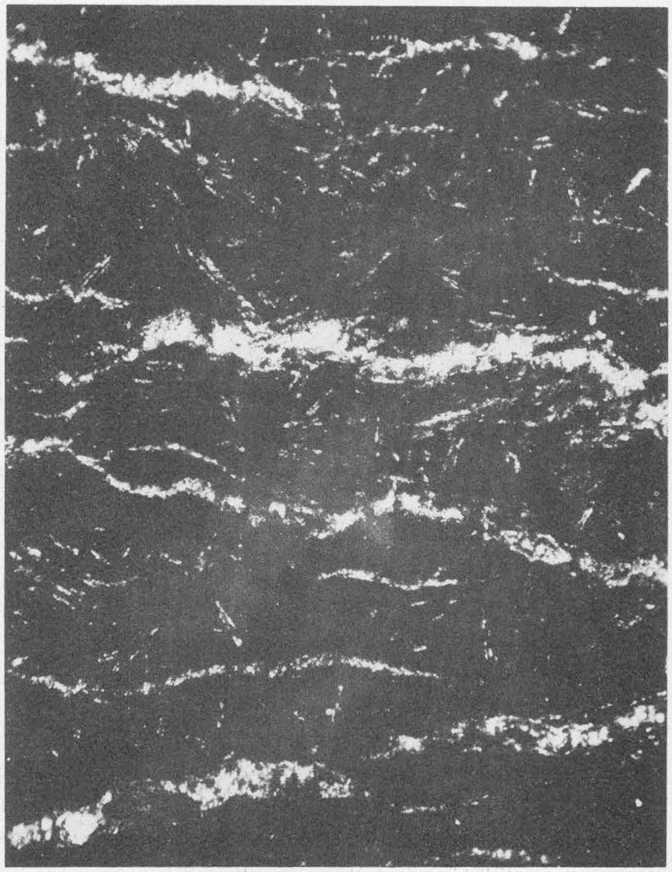

FIGURE 31.—Microscopic appearance of chilled border of diabase sill, Jackpile mine. Uranophane is along sinuous primary longitudinal joints. Plane-polarized light, × 90. Photograph by Richard B. Taylor.

Hydrous iron oxides, probably after pyrite, commonly are abundant in zones an inch thick directly above and below the sills. Many thin sections prepared from rocks sampled within a few inches of a sill contain abundant fine-grained chlorite; in some thin sections small amounts of ragged fine-grained biotite have been identified. In addition, a small quantity of coarse colorless highly birefringent mica, possibly muscovite, appears to have formed at the expense of fine-grained clay minerals.

SAINT ANTHONY MINE

The Saint Anthony mine is on the northeast end of the Paguate–Saint Anthony group of deposits (pl. 3). It is most easily reached by a road that extends east from the Laguna–Paguate road at a point about 2½ miles north of Laguna. The uranium deposit, known as the M–6 ore body, is below the water table and is worked underground through a shaft about 275 feet deep.

Because the shaft was not sunk until October 1956, at the end of the last complete field season of this project, the Saint Anthony mine was not mapped. Our knowledge of the deposit is based on drill data furnished by the Saint Anthony Uranium Corp., and on data acquired on a brief trip by the authors through the mine in April 1958. Only general features of the deposit are described.

The M–6 ore body is the largest of several small deposits in a narrow east-trending group about 1½ miles long (pl. 3). The small, so-called Hanosh deposits are at the east end of the group. Most of the deposits are indicated by single ore holes and can be considered as part of a broad low-grade zone that surrounds the M–6 ore body. A few ore holes were drilled north and south of the M–6 ore body. Anaconda's L–Bar deposit, which is probably somewhat larger than the M–6 ore body, is about 7,000 feet to the north-northwest.

The ore is in the Jackpile sandstone, which in the mine area is about 90–130 feet thick. The Jackpile isopachs in this area show several circular lows and highs, but no particular elongations that might reflect channels or Jurassic folds (pl. 3).

Strata in the area of the Saint Anthony mine dip gently northwestward, but contours (5-ft. intervals) drawn on the top of the Dakota Sandstone by geologists of the Saint Anthony Uranium Corp. also show a small structural terrace over the M–6 ore body, and possible closure of one contour on the northeast side of the deposit. Other more pronounced terraces in the vicinity do not have associated uranium deposits. The east-trending group of deposits that includes the M–6 ore body, the Hanosh deposits, and numerous other small deposits is oriented at a wide angle to the trend of the structure contours.

The M–6 ore body is roughly equidimensional in plan and about 1,000 feet in diameter (fig. 32). In places it is as much as 25 feet thick, but its average thickness is considerably less. Because figure 32 was constructed wholly from drill data, at 100-foot centers, connections between some layers may be in error. Most of the ore is in the central part of the Jackpile sandstone, and apparently nowhere is it at the bottom or top of this unit. The deposit consists largely of subhorizontal interconnecting layers, none of which extends through the whole deposit. Individual ore layers are strongly undulant, with as much as 35 feet of relief in a horizontal distance of about 300 feet; undulations have little apparent relation to the thickness variations of the Jackpile sandstone or to the structural relief of the Dakota Sandstone.

The abrupt changes in ore thickness probably reflect roll structures. In places, especially in the southern part of the deposit, the rolls were located by drilling that was so closely spaced that it cannot conveniently be shown in figure 32. Here, "barren" holes are less than 50 feet from ore holes that penetrate as much as 20 feet of ore. In one place in the north-central part of the deposit, thickness and ore grade range from 2 feet of low-grade material to 25 feet of ore that averages 0.26 percent U_3O_8 within a horizontal distance of 50 feet.

The ore is gray to black, and from its general appearance it is undoubtedly similar in composition to Jackpile ore. The few data available indicate that the vanadium and calcium carbonate contents of the ore are low. Few assays are in excess of 1.0 percent U_3O_8, and most are well below 0.5 percent U_3O_8. A few high-grade assays represent ore nearly 5 feet thick, but most represent ore a foot or less thick. According to U.S. Atomic Energy Commission production data, 2,658 tons of mined ore averaged 0.20 percent U_3O_8; vanadium was not reported.

The ore in the Saint Anthony mine, like that in the Jackpile, tends to be concentrated along bedding planes, but it shows many forms that cut sharply across bedding planes. Because the ore in the walls of the Saint Anthony mine is generally less oxidized and cleaner than that in the walls of the Jackpile, the typical ore habits can be seen to better advantage (fig. 33*B*,*C*,*D*). Ore rods, which are common, are locally cone shaped (fig. 33*B*), unlike any that have been seen in the Jackpile deposit. The irregular patchworks of ore have the appearance of having been partly leached (fig. 33*C*,*D*) and locally show evidence of two generations of ore. The patchwork ore shown in figure 33*D*, for example, may have formed by partial irregular leaching of ore that once impregnated a larger volume of sandstone, and the wispy broadly S-shaped roll may have formed subsequently.

WINDWHIP MINE

The Windwhip mine, a small open pit a short distance west of the Jackpile open pit (pl. 3), is one of several small satellite bodies around the Jackpile deposit. Since the mapping in 1955, the mine has been buried by dumps extending from the Jackpile mine.

A total of 2,788 tons of ore was shipped from the mine before 1955; this ore averaged 0.31 percent U_3O_8 and 0.17 percent V_2O_5 (table 6). The $CaCO_3$ content averaged about 1.2 percent, considerably more than that of the Jackpile ores.

The Windwhip deposit is in the upper part of the Jackpile sandstone, about 15 feet below the base of the Dakota Sandstone. It is at about the same elevation and stratigraphic position as the so-called Windwhip horizon in the Jackpile mine (pl. 6B).

Because it was only a short distance below the surface before mining, the Windwhip deposit is more oxidized than the Jackpile but is otherwise similar to the Jackpile in appearance and composition. Hydrous iron oxides are locally abundant, and minerals of hexavalent uranium probably contain much of the uranium. Nevertheless, the form of the deposit is outlined by its gray color—contrasting with the white or light tan of the host sandstone.

The general form of the deposit—several well-defined rolls—and local ore concentrations along bedding planes were shown by Hilpert and Moench (1960, fig. 13). A

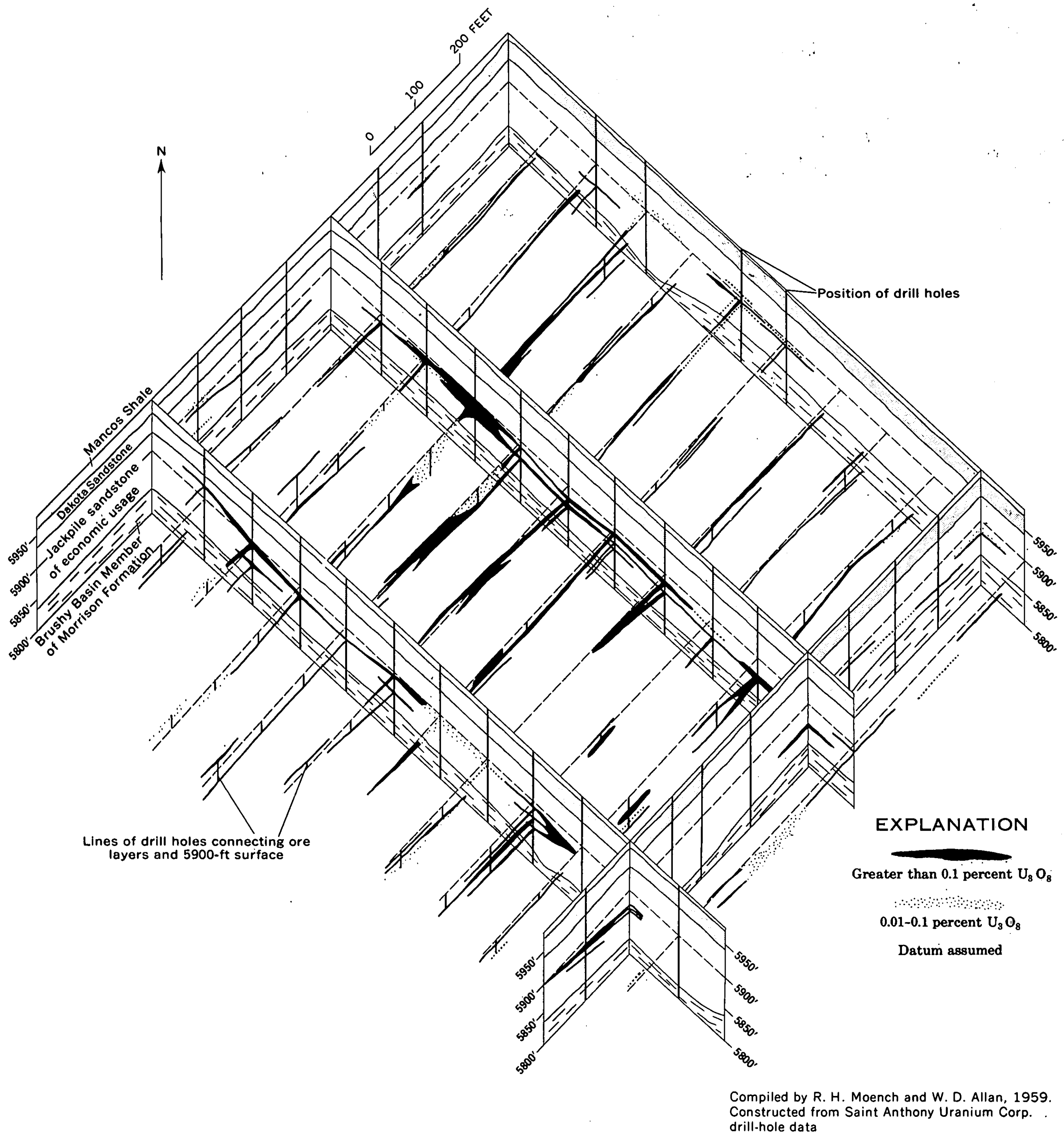

FIGURE 32.—Shape of the M-6 ore body, Saint Anthony mine.

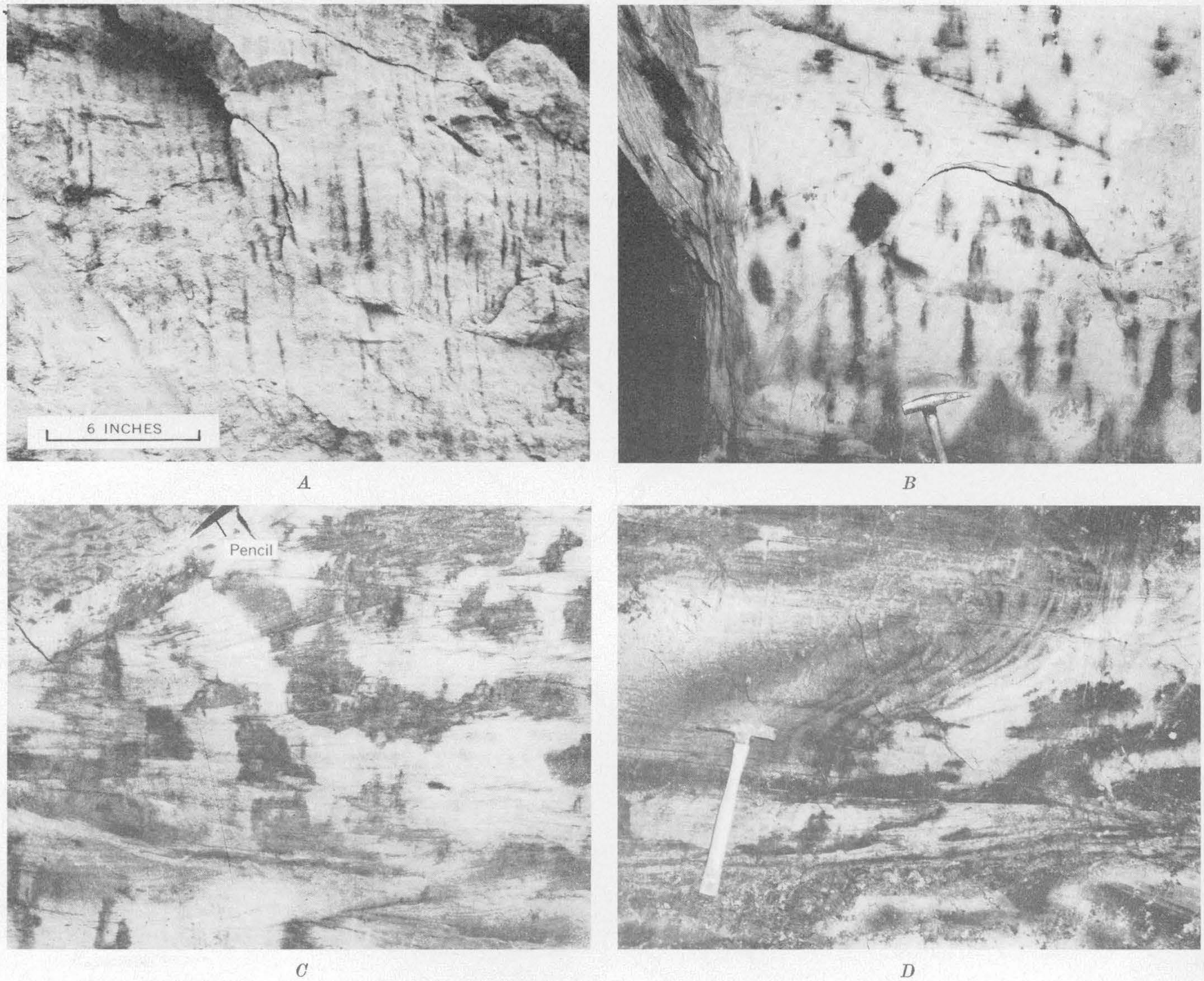

FIGURE 33.—Features of black ore, Jackpile and Saint Anthony mines. *A*, Typical ore rods, Jackpile mine. *B*, Ore rods and cones, Saint Anthony mine. *C*, Patchwork ore in crossbedded sandstone, Saint Anthony mine. *D*, Irregular ore patches apparently crossed by younger wispy S-shaped roll.

small part of the deposit is shown at a larger scale in figure 20 of the present report. Axes of the rolls trend about N. 60° W., about parallel to the average strike of the crossbedding.

WOODROW MINE

The Woodrow mine, about 1 mile east of the Jackpile mine (pl. 33), was discovered in 1951 by aerial radiometric prospecting. The deposit is in a nearly vertical sandstone pipe and was mined through a vertical shaft about 230 feet deep and two lateral shafts at the 100- and 200-foot levels (Wylie, 1963, fig. 1). Mining began in 1954 and ended in 1956, when the square-set timbering collapsed.

The Woodrow mine was described briefly by Hilpert and Moench (1960, p. 456), and in greater detail by Wylie (1963, p. 177). The following description summarizes Wylie's data and our observations. The mineralogy and ore textures were previously described (p. 58, 84, this report; Wylie, 1963, p. 179–181; and Moench, 1962b).

According to U.S. Atomic Energy Commission production data, 5,326 tons of ore has been shipped from the mine (table 6). This ore averaged 1.26 percent U_3O_8, 0.04 percent V_2O_5, and 1.4 percent Ca CO_3. According to Wylie (1963, p. 177), ore from above the 100-foot level averaged 1.53 percent U_3O_8 and 0.05 percent V_2O_5, whereas ore from below the 100-foot level averaged 0.32 percent U_3O_8 and 0.03 percent V_2O_5.

The pipe crops out in the Jackpile sandstone and probably extends more than 200 feet in depth, the maximum depth of mining. Drilling, however, has failed to intersect the pipe at greater depths. The pipe is circular in plan and ranges from about 24 to 34 feet in diameter; from the surface to a depth of 50 feet it plunges about 67° S. 50° E., and below this depth it spirals to a plunge of about 83° N. 45° E. (Wylie, 1963, p. 177, and fig. 1).

The interior of the pipe is a compact mixture of broken mudstone and sandstone from the Jackpile sandstone and Brushy Basin Member of the Morrison. Jackpile sandstone is dominant in the upper part of the pipe, whereas mudstone is dominant in the lower part. Though commonly called a breccia, the sandstone and mudstone fragments tend to be rounded or rather ragged and irregular in shape rather than sharply angular, and the mudstone or sandstone in which they are embedded is compact; vugs are sparse. The border of the pipe is locally marked by a complex pattern of anastomosing ring faults (pl. 7) or by the broken edges of the surrounding strata. According to Wylie (1963, p. 177), the strata around the pipe do not sag inward, contrary to the illustration shown by Hilpert and Moench (1960, fig. 15).

The bottom of the Jackpile sandstone within the pipe is either 30 feet or 45 feet lower than the bottom of the Jackpile outside the pipe, depending upon which zones are correlated.

The high-grade ore in the upper part of the pipe is concentrated along the ring faults; it locally permeated the interior of the pipe, in zones where the sandstone was thoroughly broken, and locally extended as much as 10 feet into the surrounding strata (Wylie, 1963, p. 177). Below a depth of about 90 feet, ore is confined to the interior of the pipe; in the upper part of this zone the ore permeates and darkens the mudstone, whereas in the lower part it is largely confined to the interstices of fragments (Wylie, 1963, p. 177).

The ore along the boundary ring faults occurs as pore fillings and replacements, not fissure fillings (p. 84). Vugs have locally been filled with ore minerals (Moench, 1962b), but such occurrences are rare.

The outcrop (pl. 7) is thoroughly weathered. Sulfides are absent and hydrous iron oxides are abundant; viewed in thin section, many specimens are thoroughly cemented with silica, much of which is opal. As shown on plate 7, the outcrop is highly radioactive, particularly in an arcuate zone that roughly conforms with the arcuate fractures. The black carbonaceous material is highly uraniferous, but most of the outcrop is nearly barren of uranium.

OTHER DEPOSITS IN THE JACKPILE SANDSTONE AND BRUSHY BASIN MEMBER OF MORRISON FORMATION

Many deposits for which data are inadequate for detailed description have been found in the Jackpile sandstone and the Brushy Basin Member of the Morrison. Pertinent information is summarized here.

The Paguate deposit, a short distance west of the Jackpile (pl. 3), was discovered by core drilling in June 1956. Subsequent drilling revealed a uranium deposit almost as large as the Jackpile. By 1963 a large open pit had been developed by stripping operations, and ore was being mined.

In plan view the Paguate deposit is about 9,500 feet long and generally less than 1,000 feet wide and trends sinuously northeast (pl. 3). In the eastern part of the deposit, most of the ore is in the upper third of the Jackpile sandstone, which here is 140 to about 200 feet thick; at places ore layers abut directly against overlying Dakota Sandstone (Kittel, 1963, p. 170 and fig. 4). In the western part, most of the ore is in the lower two-thirds of the Jackpile sandstone, which here is about 80–140 feet thick (Kittel, 1963, p. 170). The Paguate deposit trends about at right angles to the Jackpile but is similar to the Jackpile in form, character, and composition.

One deposit about 1¼ miles east-northeast of the Woodrow mine (pl. 3) is as much as 5 feet thick and about 600 feet wide where exposed along the face of an open prospect cut. The deposit is at the base of the Jackpile sandstone, which here is only about 50 feet thick. Most of the exposed sandstone is friable, but that in the middle of the unit, well above the uranium deposit, forms a prominent bench. The bench-forming sandstone, in a strongly silicified zone as much as 15 feet thick, contains many nonradioactive gray, tan, and orange silicified logs. The uranium deposit, at the base of the Jackpile sandstone, is composed mostly of uraniferous carbonaceous matter, though yellow-green minerals of hexavalent uranium are exposed locally. Carbonaceous matter forms wispy rolls, sparse to abundant spots about 1 mm in diameter, and nearly pure botryoidal nodules.

A small unprospected uranium-vanadium deposit is exposed about 2.8 miles S. 35° W. of the Woodrow deposit (pl. 3). Its base is about 30 feet above the base of the Jackpile sandstone, which here is about 100 feet thick. The deposit is a series of large rolls, which aggregates about 20 feet high and 40 feet wide (fig. 34). The top of the zone is about 2 feet below a thin mudstone bed. On the surface the deposit is dark gray, although it contains tyuyamunite. Some of the gray coloring is imparted by carbonaceous material, but much is imparted by dark-brown fine-grained vanadium clay, which completely fills pore spaces in the darkest parts of the deposit. Two samples of the darkest material contain 0.086 and 0.061 percent uranium and 1.01 and 0.50 percent vanadium, respectively.

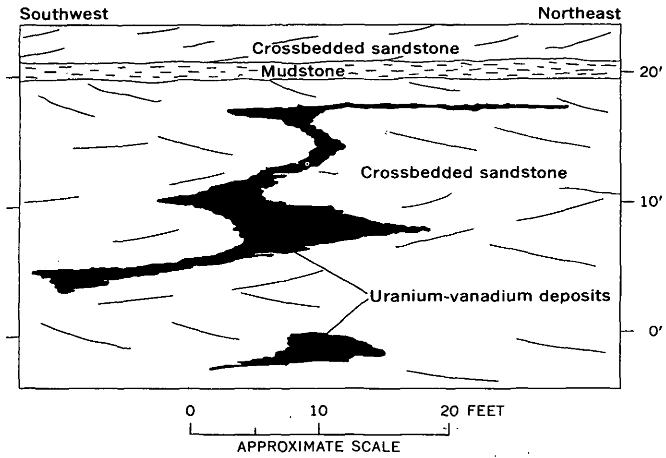

FIGURE 34.—Sketch of small uranium-vanadium deposit in Jackpile sandstone about 2½ miles south-southwest of the Jackpile mine.

On Seama Mesa, at the west side of the district, a deposit that is exposed intermittently for 600 feet along an open cut has been prospected just below the Dakota Sandstone (pl. 3). Most of the deposit is in a sandstone stratum in the Brushy Basin Member of the Morrison, but it locally extends upward into a sandstone lens of unknown correlation between the Brushy Basin and Dakota strata. The sandstone lens is 5–15 feet thick and is composed of quartz sandstone and local quartz pebble and cobble conglomerate; it locally contains abundant coalified plant debris. Much of the mineralized sandstone is pink or violet and contains finely disseminated hematite and sparse yellow minerals of high-valent uranium and vanadium. In places the yellow minerals coat joints.

On the west side of Mesa Gigante, about 4 miles S. 10° E. of Piedra Lumbre (pl. 3), a small deposit was found near the top of a sandstone unit in the Brushy Basin Member. The sandstone unit is about 50 feet thick and is fairly continuous; its top is about 100 feet below the base of the Jackpile sandstone. The deposit, which has not been prospected, is associated with silicified and coalified logs.

CHAVEZ MINE AND OTHER DEPOSITS ON THE EAST SIDE OF MESA GIGANTE

On the east side of Mesa Gigante several small deposits occur in sandstone near the bottom of the Morrison Formation (pl. 3). Some of these have been prospected, but only the Chavez has produced ore. Most of these deposits have similar host rock, composition, and association with fragmental carbonaceous material; three are described here.

The Chavez mine is a short distance southwest of the small Navajo Indian village of Canoncito and can be reached by a jeep road that extends almost to the mesa rim and, thence, by a foot trail that extends north about half a mile from the end of the road. The workings (fig. 35) consist of a short adit and a drift. The mine is close to the surface throughout, and is in an area that is extensively covered by colluvial debris. The area is well drained, so the deposit has undoubtedly been above the water table for a considerable period of time.

The Chavez mine produced 190 tons of ore, according to U.S. Atomic Energy Commission records. This ore averaged 0.21 percent U_3O_8 and 0.56 percent V_2O_5 (table 6). Vanadium is much more abundant relative to uranium than in any of the other mined ores in the district. The high relative vanadium content is also shown by three selected specimens: two contain 0.41 and 0.56 percent uranium and 0.90 and 0.99 percent vanadium, respectively, and one contains 4.85 percent uranium and 3.51 percent vanadium. The calcium carbonate content is also high, averaging 9.4 percent, which is much more than in the other Morrison ores of the district.

The Chavez deposit is in arkosic sandstone in the Westwater Canyon Member of the Morrison Formation, which in the mine area is as much as 100 feet thick, including several thin mudstone splits. The sandstone is fine to coarse grained and poorly sorted and is locally well cemented with calcite; in places it contains abundant fragmental plant remains. In the mine the host sandstone is separable into an upper, coarse-grained sandstone and a lower, fine- to medium-grained sandstone. Both units, particularly the upper, contain coalified plant debris. The debris in the upper unit is unmineralized.

The Chavez deposit has the form in section of a flattened S-shaped roll (fig. 35). The axis of the roll trends northwest parallel to the general strike of crossbedding. The projection of ore in plan appears as a long narrow trace (fig. 35); datum for the projection is about 3½ feet above the floor of the mine.

The ore is highly oxidized, and carnotite is the most abundant uranium ore mineral. Black uraniferous carbonaceous matter that coats sand grains is abundant but does not give an X-ray pattern. Vanadium is in carnotite and vanadium clay. Thin sections of the highest grade material show sandstone that is almost wholly cemented by fine-grained brown pleochroic moderately birefringent vanadium clay, which gives an X-ray pattern similar to that of roscoelite.

The Section 4 prospect, a short adit about 3½ miles north-northwest of the Chavez mine (pl. 3), is in a thin lens of fine-grained carbonaceous sandstone in the upper part of the Recapture. Member of the Morri-

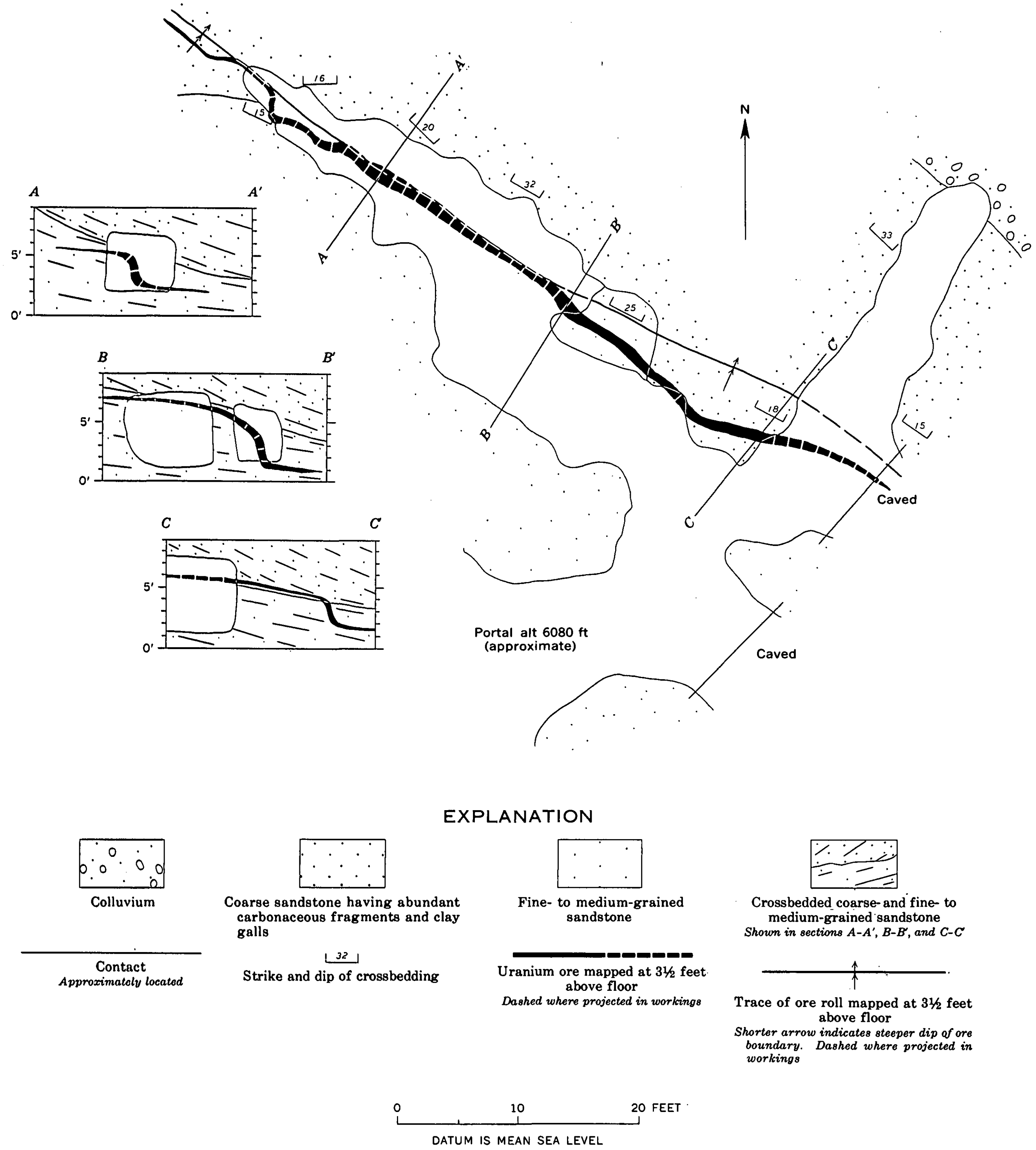

FIGURE 35.—Geologic map and sections of the Chavez mine.

son. At the portal the lens is about 5 feet thick, but it pinches out about 60 feet north and 20 feet south of the adit. The uranium deposit is about 3 inches thick and follows the contact between the carbonaceous and conglomeratic sandstones. The carbonaceous material in both units is fine-grained coalified plant debris. The carbonaceous sandstone above the deposit is slightly radioactive, but no correlation is apparent between abundance carbonaceous material and radioactivity.

SANDY MINE

The Sandy mine is in the southern part of the Laguna district, about 3 miles southwest of Mesita (pl. 3); it is accessible from U.S. Highway 66 only by poor road. The mine includes many small uranium deposits in a small area in the Entrada Sandstone and limestone of the Todilto Formation.

The Sandy mine, discovered in 1950 or 1951, is not economically significant, having shipped only 939 tons of ore that averaged a scant 0.12 percent U_3O_8 and 0.14 percent V_2O_5 (table 6). The mapping of the mine area by planetable at a scale of 1 inch: 200 feet, combined with Anaconda Co. drill data, delineated the distribution of uranium (pl. 8).

LITHOLOGIC UNITS

The Sandy mine is underlain by the Entrada, Todilto, and Summerville Formations, all intruded by diabasic sills and a few dikes.

The Entrada Sandstone in this area consists of only the middle siltstone unit and the upper sandstone unit. The base of the siltstone is not exposed in the mine area, but nearby exposures indicate that the siltstone is probably about 80 feet thick. The upper sandstone unit is about 95 feet thick. In most of the area the upper approximately 30 feet of the unit is nearly white, whereas the lower part is red; at places near the diabase dikes and sills the lower part has been pyritized and changed from red to tan or very pale orange.

The Todilto in the mapped area consists of a lower unit of limestone and an upper unit of leached gypsum breccia. The limestone is about 30 feet thick in the structurally low part of the area, and thins northward to about 15 feet in the structurally high area. It is divisible into a lower zone of stratified limestone and an upper zone of massive limestone. The thickness of the stratified limestone ranges from 15 to 18 feet, but the thickness of the massive limestone is more variable and accounts for much of the thickness variation of the unit. The leached gypsum breccia is about 15 feet thick in the northern part of the area, but ranges from zero to more than 30 feet in thickness farther south.

The Summerville Formation is composed of interstratified sandstone and mudstone or siltstone. In the northern part of the area mudstone or siltstone is at the base of the unit, but farther south sandstone directly overlies the Todilto.

Many diabase sills and a few dikes, which interconnect (pl. 8), intruded the sedimentary rocks and metamorphosed them at the contacts. The dikes, which are 8 feet or less thick, strike about north and are nearly vertical. The sills, which are less than 1 foot thick to slightly more than 80 feet thick, have a far greater aggregate volume than do the dikes. The sills, though subparallel to the stratification, locally break at a low angle across stratigraphic units. Deformation by diabasic magma was so gentle in most places that the preexisting structural features are well preserved.

STRUCTURE

The dominant structural feature at the Sandy mine area, disregarding that related to diabase, is a south-facing Jurassic monocline whose limb dips as much as 12° S. (pl. 8, section *A–A′*). On this steep limb are several smaller discontinuous structural terraces which are best exposed near Pits I and IV (pl. 8). In addition, the Todilto limestone is deformed by many intraformational folds, which tend to be largest in the structurally low areas and account for some of the thickening of the limestone there. Though sinuous, the axes of these folds tend to parallel the larger structures.

The Cenozoic joint pattern contains one set that trends north, two sets that trend slightly east and west of north, and one set that trends east (fig. 13). The joint sets in the limestone, sandstone, and diabase differ in some respects, but their similarities suggest a common origin.

DISTRIBUTION AND CHARACTER OF URANIUM DEPOSITS

The distribution of uranium deposits in the Sandy mine (pl. 8) was determined by the use of a scintillation counter, by observation of exposed uranium minerals, and by drilling by the Anaconda Co. In general, most of the deposits are confined to an elliptical belt at least 3,000 feet long and about 1,200 feet wide. The belt of deposits is almost wholly on the steep limb of the main Juarassic monocline; it is oriented northeastward about parallel to the monocline. The original preerosion length of the belt is not known; but the indicated width of 1,200 feet is probably representative, because the host rocks are well exposed on either side farther north and south. The 3,000-foot length is a minimum, because on the northeast end the host rocks have been eroded, and on the southwest end (west of the mapped area shown on pl. 8) they have not been prospected thoroughly.

The largest deposits are clustered near the north side of the belt, so that the northern limit of the belt of deposits is sharply defined. To the south the deposits become smaller and more widely spaced; therefore the southern boundary is only arbitrarily defined. An isoradioactivity line could be drawn with reasonable assurance only on the north side of the belt. North of the isoradioactivity line the radioactivity of the host limestone and sandstone, as determined by scintillation counter, is generally equal to or less than 0.005 milliroentgens per hour, whereas south of the line it is variable, but mostly above 0.005 milliroentgens per hour.

In the structurally high area, near the anticlinal bend of the monocline and on the limb, most uranium deposits are near the top of the Entrada Sandstone; locally they extend upward into the limestone. In the structurally lower area, deposits are well within the stratigraphically higher limestone. Thus, any one section across the belt would show that the deposits are in a narrow zone that passes from the Entrada in the structurally high area to the Todilto in the lower area (section *B–B′*, pl. 8 this report; Hilpert and Moench, 1960, fig. 15). The group of deposits, in other words, is tilted toward the syncline less steeply than the host rocks.

The deposits in limestone, none of which have been exploited, are largely associated with intraformational folds. The deposits are probably elongate and sinuous like the folds, and possibly split into two or more deposits where the folds split. They are characteristically low grade; very few samples assayed more than 0.1 percent uranium, and samples from only two of the many holes that the Anaconda Co. drilled revealed more than 0.08 percent uranium. The highest grade samples contained only 0.22 percent uranium in a 2-foot interval.

Figure 36 illustrates a typical mineralized intraformational fold. The uranium deposit, outlined by the one-tenth milliroentgen isoradioactivity line, is largely in the massive thick-bedded limestone in the center and at the base of the fold. Chemical data substantiate the isorads fairly well (fig. 36). The uranium deposit is separated into three parts by two diabase sills; but as the lower sill is about 20 feet thick, the lowest segment of the deposit is not shown in figure 36.

Minerals of hexavalent uranium, mostly tyuyamunite or metatyuyamunite, are abundant; carnotite is sparse. Much of the vanadium is in vanadium clay along the bedding planes in the limestone.

Deposits in the Entrada Sandstone are semitabular, roughly parallel to the stratification, and are generally larger and higher grade than deposits in the limestone. Their tabular form is modified by rolls. Drilling by the Anaconda Co. revealed considerably more ore-grade material in the Entrada than in the limestone, and

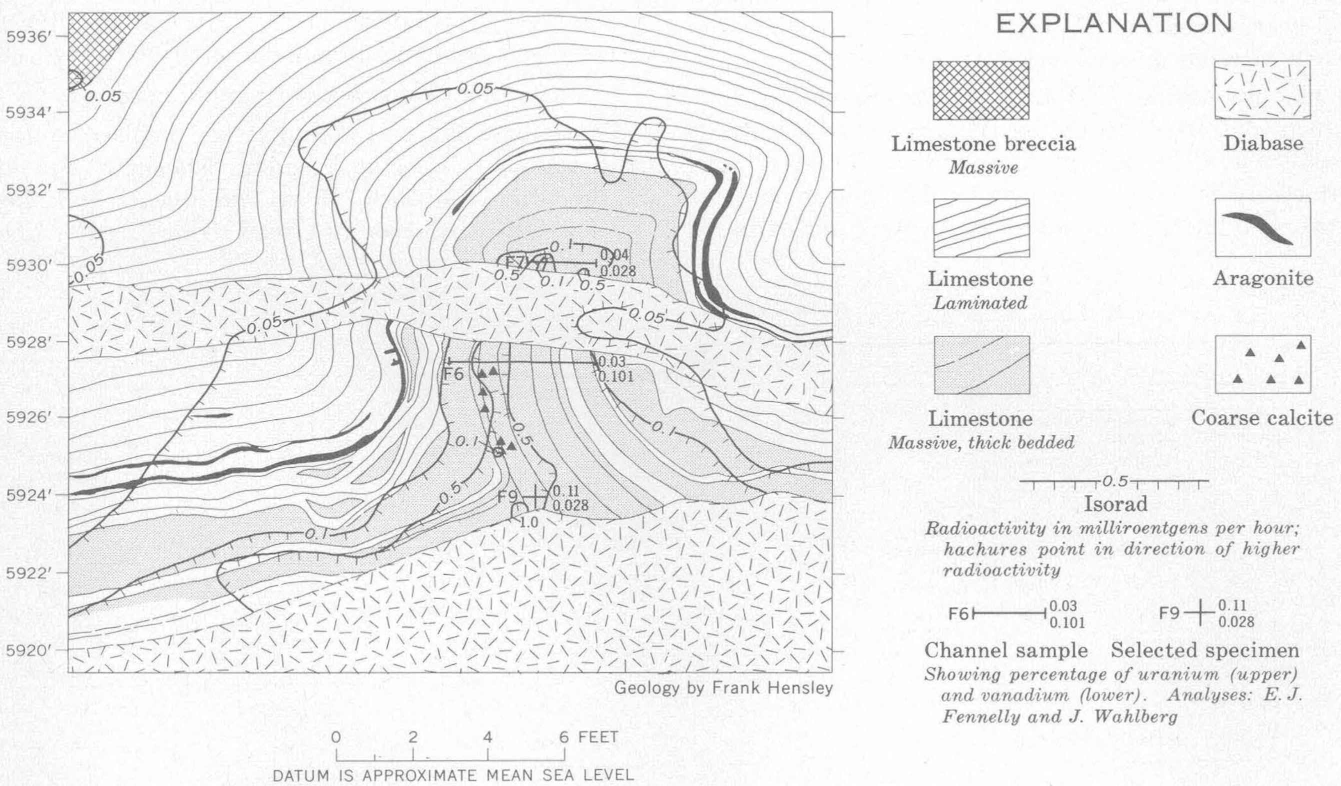

FIGURE 36.—Section across uranium deposit in Todilto limestone, Sandy mine.

assays of several samples revealed more than 1 percent U_3O_8.

The deposit prospected by Pit II (pl. 8) is a single roll that connects two thin tabular layers (fig. 37). In a gully northeast of the prospect pit, the deposit is a thin tabular horizontal layer that is exposed about 7 feet below the Todilto-Entrada contact. In the pit this layer thickens and curves sharply upward in a roll and thence flattens farther southwest in a thin layer about 2 feet below the formational contact. As seen in outcrops farther west, this layer rises stratigraphically and crosses the contact near the anticlinal bend of the monocline (pl. 8). The roll is about 5 feet high and 5 feet wide and trends about N. 45° W. This direction is not parallel to any known sedimentary or tectonic structural feature.

The deposit is largely oxidized, and probably all of its uranium is in the hexavalent state. Uranium is dominantly in carnotite, and vanadium is partly in vanadium clay. The higher grade ore sample from the deposit contains 0.044 percent uranium, and 0.576 percent vanadium (fig. 37).

The Pit I deposit is the largest single deposit in the Sandy mine and is the chief source of ore mined in this area. It is on the west end of a narrow east-trending belt of deposits about 600 feet long (pl. 8) which, prior to erosion, may have been a single deposit. At its west end the belt is well below the Entrada-Todilto contact, but near its east end it is directly under the contact and locally extends upward into the limestone.

The ore exposed in Pit I is various shades of gray, which contrasts with the nearly white barren Entrada Sandstone, and is only partly oxidized. Relatively low-grade ore is mostly homogeneously light to medium gray, but the highest grade ore is black and strongly mottled. Exposed near the west end of the deposit are a few 1- to 2-inch-thick concretions of uraninite surrounded by pyrite that are flattened parallel to the bedding. The dark shades of the ore are given by coffinite, uraninite, and vanadium clay; carbonaceous matter is sparse. The highest grade ore specimen contained 1.38 percent uranium and 0.5 percent vanadium; the average ore grade is about 0.1 percent uranium and 0.08 percent vanadium (table 6).

The general form and stratigraphic position of the deposit in Pit I are shown in figure 38. Section *A–A′* is based on logs of six drill holes, as well as a map of the surface exposure. The other three sections are based largely on a map of the surface exposure. Drill holes that are outside the pit and are not on the lines of section outline the limits of the deposit. The low-grade halo is mostly below the Entrada-Todilto contact; only in the westernmost section does the halo rise as high as this contact.

Roll structures have gradational boundaries marked only by a subtle darkening of the rock. A sequence of nine samples across the concave roll boundary exposed in the north side of the pit (fig. 39) shows a gradual increase in uranium and vanadium content from light to darker sandstone. The sample representing the full thickness of mineralized rock and the samples taken above and below the deposit also confirm the visible distribution of ore. The roll axis trends about parallel to the cross-stratification in the Entrada, which here strikes about east and dips as much as 30° S.

RELATION OF DIABASE TO URANIUM DEPOSITS

The diabase sills and dikes intrude, displace, and locally metamorphose the uranium deposits. (See fig. 36, this report; Moench, 1962a; and Moench and Meyrowitz, 1964.) At least five holes drilled by the Ana-

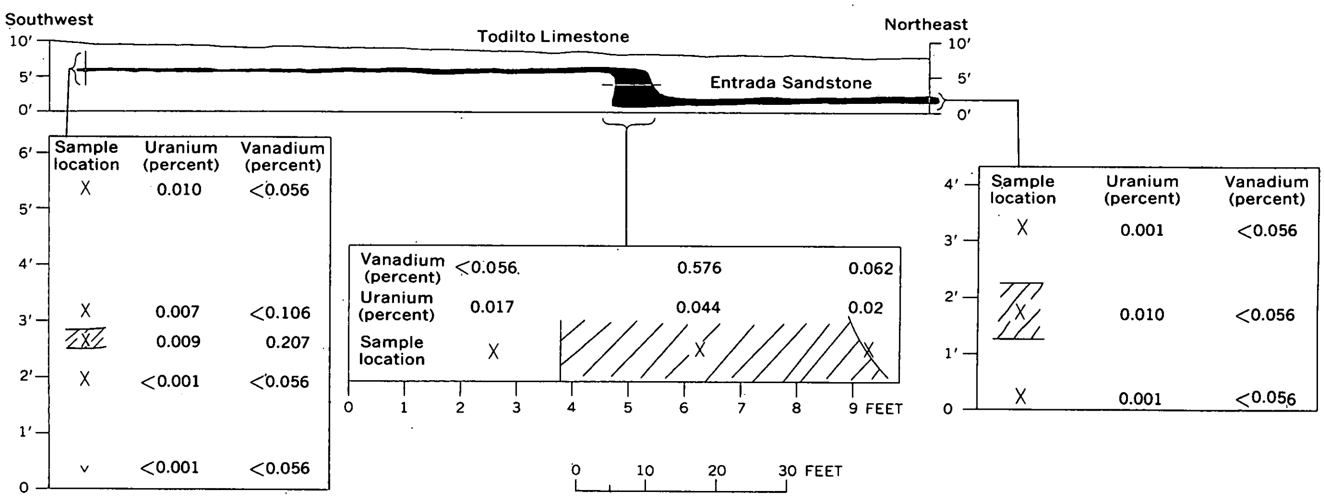

FIGURE 37.—Pit II deposit, Sandy mine, showing sample distribution and uranium and vanadium contents. Analysts: E. J. Fennelly and J. S. Wahlberg.

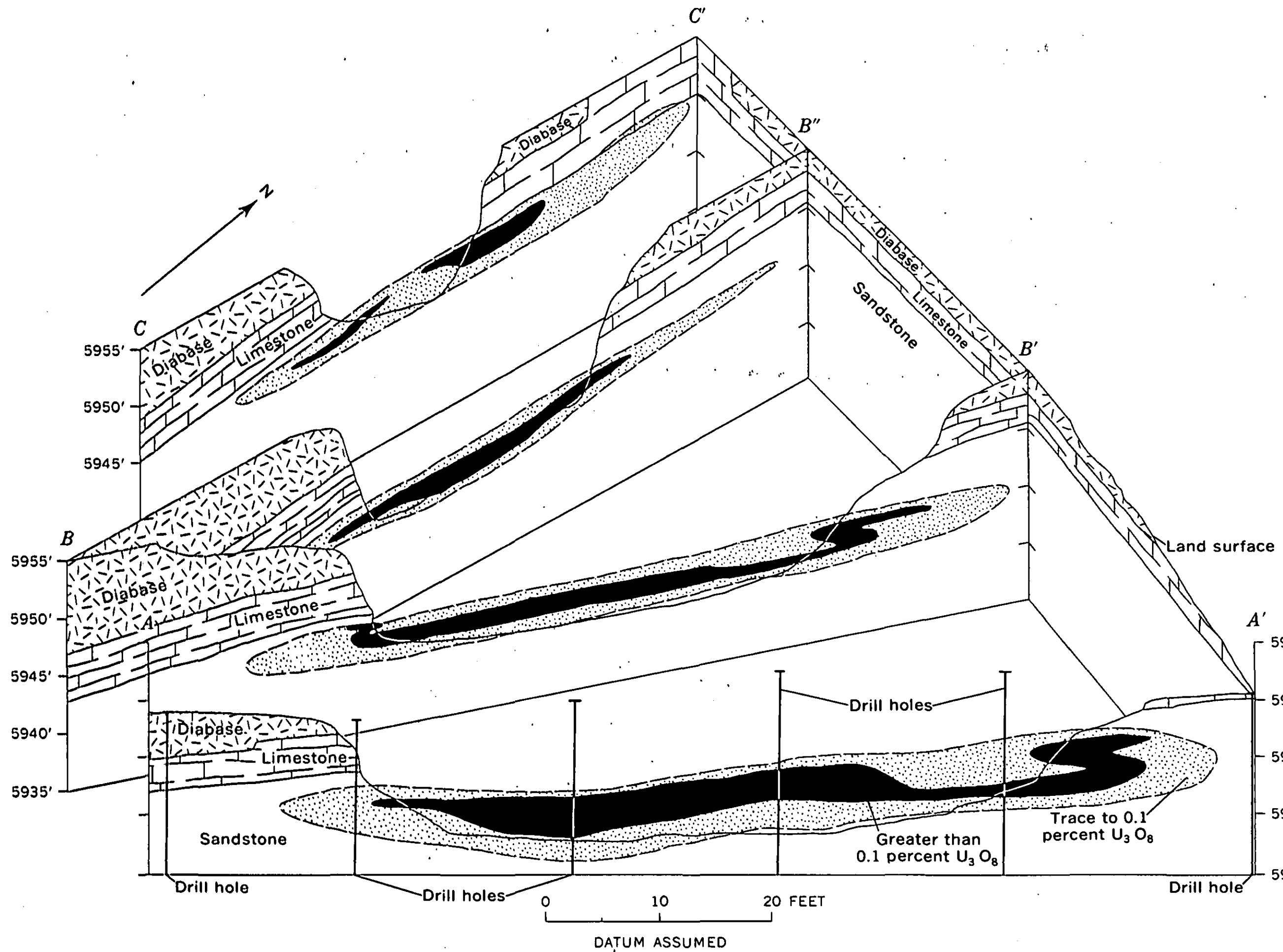

FIGURE 38.—Uranium deposit in Pit I, Sandy mine. Solid line in each profile is outline of open pit.

conda Co. penetrated mineralized limestone or sandstone that is intruded and separated by 18- to 54-foot-thick unmineralized diabase sills. An inclusion of mineralized limestone in the diabase was mined in Pit III (center of section *A–A′*, pl. 8); drilling revealed a uranium deposit directly below the sill.

Amount and distribution of uranium in the sills here and in the Jackpile mine are similar in some respects. Although the sills in the Sandy mine nowhere are ore grade, uranium does appear to be concentrated in the chilled borders where the sills intrude deposits. Chilled borders in contact with the uranium deposits shown in figure 36 contain as much as 0.0055 percent uranium, whereas diabase elsewhere in the mine area, but far from a known uranium deposit, contains 0.0005 percent or less uranium (analyst, Dorothy L. Ferguson).

CRACKPOT MINE

The Crackpot mine is in the southern part of the Laguna district, about 7 miles southwest of Laguna (pl. 3); it is accessible by poor roads south from Mesita, on U.S. Highway 66, and east from the road to Acoma.

The deposit, mined by a small open-pit operation, is the only one in limestone of the Todilto Formation that has produced a significant amount of uranium ore. In August 1955, when this study was made, the deposit was mined out; its total production was 3,214 tons of uranium ore averaging 0.13 percent U_3O_8 and 0.33 percent V_2O_5 (table 6).

The unoxidized ore minerals—uraninite(?), vanadium clay, and pyrite—are distributed along bedding planes in the stratified limestone and along grain boundaries in the massive limestone. Tyuyamunite appears to be the dominant mineral of hexavalent uranium.

The limestone at the Crackpot mine is distinctly separable into a stratified unit 6–8 feet thick and an overlying massive unit 15 feet or more thick. In the stratified unit siltstone laminations at intervals of about 2 inches give the rock a slabby or platy parting. The massive unit is composed of relatively massive coarser grained limestone that is traversed by irregular subhorizontal deformed bedding planes.

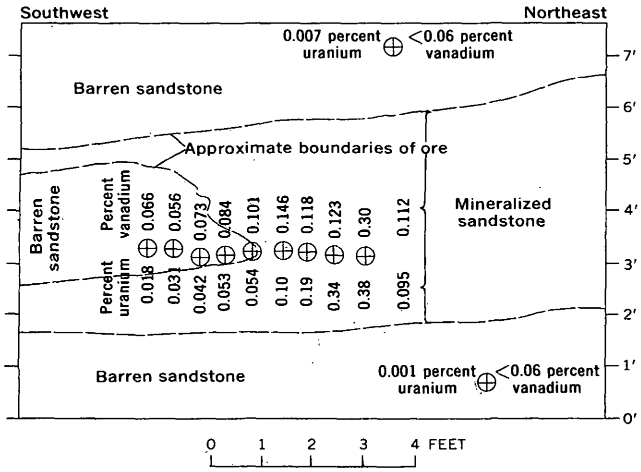

FIGURE 39.—Small roll in north side of Pit I, Sandy mine, showing sample distribution and uranium and vanadium content. Analysts: E. J. Fennelly, W. D. Goss, and H. H. Lipp.

The top of the Entrada Sandstone immediately north of the mine strikes west-northwest and dips gently north, forming a north-facing monocline which is probably related to the Jurassic system of folds (pl. 9). In the mine and to the west and south this horizon is characterized by several low-amplitude small domes and basins. The dominant structural feature formed by the top of the Entrada in the mine is a doubly plunging northwest-trending anticline, which is part of a broad fold that diverges southeastward from the trend of the monocline. In the open pit the major structures in the Todilto reflect the form of the top of the Entrada fairly well, but minor structures commonly have very different orientations. The top of the stratified limestone unit only approximately conforms to the top of the Entrada.

The stratified limestone is deformed by many small intraformational asymmetric folds whose axial planes dip at low angles toward their structurally raised sides (pl. 9). Their axes bear east-west to northeast, and rarely northwest. The axial plane of each minor, asymmetric fold passes downward within a foot or two into a bedding-plane fault, or into a low-angle thrust fault that breaks across two or three beds. The fact that these faults have slickenside striae that are oriented about normal to the fold axes (pl. 9) suggests that the minor folds and faults are directly related.

Two northwest-trending fracture zones in the stratified limestone, which are exposed in the open pit (pl. 9), are about 5 feet high and a few feet wide and dip steeply toward one another. Openings along the fractures are as much as 4 inches wide and are filled with calcite and dolomite. Carbonate-filled fractures have been displaced laterally along bedding-plane faults. Slickenside striae are conspicuous on these faults where they cut the steep fractures. Some slickensided bedding-plane faults, however, are sharply cut and slightly displaced by steep calcite- and dolomite-filled fractures. These relations indicate that the two fracture zones formed contemporaneously with bedding-plane slippage and probably during the formation of the small asymmetric folds. Because of the width of the fractures and their limited vertical extent, they are inferred to have formed by shrinkage of bedded limestone during consolidation. Their orientation might have been governed by the doubly plunging anticline that is expressed by the top of the Entrada (pl. 9).

Cenozoic joints are abundant in the open pit, and the pattern is consistent with that recognized throughout the district (pl. 4). Except for local coatings of high-valent uranium minerals and some soft fine-grained carbonate minerals, these joints are not mineralized.

Plate 9 shows the areal distribution of the uranium ore and of the halo of low-grade material surrounding the ore. The ore body occupies the crest of the main northwest-trending doubly plunging anticline, and a narrow arm of the deposit extends along the southwest-trending extension of the anticline. The ore body is about 110 feet long and 60 feet wide, except in the extension; drill-hole data indicate that the deposit is about 11 feet thick near the center. The halo of low-grade material extends from the deposit in three arms. Two arms extend west-northwest and east, respectively, from the ore body, and approximately conform with structural highs. The third extends southeast beyond the southwest extension of the ore body and appears to have little relation to structural features.

The Crackpot deposit is shown in three dimensions in the fence diagram on plate 9, which was compiled from maps of the open pit and from Anaconda Co. drill-hole data. The ore body is dominantly in the stratified limestone, but it extends upward several feet into the massive limestone. The bottom of the deposit is locally on the top of the Entrada Sandstone, but in most places it is a foot or more above this contact. The lateral boundaries of the ore body have roll-like constructions about on the contact between the stratified and massive units.

AGE OF URANIUM DEPOSITS

Many aspects of the origin of Colorado Plateau uranium deposits remain enigmatic, partly because there is no conclusive evidence of the age of uranium deposition relative to the age of major geologic events that affected the surrounding terrane. For lack of definite geologic evidence, the postulated Late Cretaceous or early Tertiary age of uranium deposits in the Uravan mineral belt, determined from lead-uranium isotope data (Stieff and others, 1953), is accepted by many plateau geologists. In spite of the discordant ages obtained from these data (Stieff and Stern, 1956), this work appears to have influenced many plateau geologists more than all other geologic evidence combined. More recent isotopic data are similarly discordant and likewise do not indicate absolute age (Miller and Kulp, 1963). The geologic relations summarized here for the Laguna district favor greater ages than are commonly postulated for other parts of the plateau. Briefly, the deposits are closely associated with Jurassic structural features and appear to be older than Cenozoic features and igneous rocks.

Uranium deposits in the Jackpile and Sandy mines were intruded and metamorphosed by Tertiary diabase dikes and sills, which are probably the oldest igneous rocks in the district. The deposits also appear to be older than the Cenozoic fractures, as these fractures have neither localized uraniferous carbonaceous matter nor influenced the trends of ore bodies. The relations between Cenozoic fractures and ore in the Laguna district are consistent with those described by Granger, Santos, Dean, and Moore (1961, p. 1188–1191) in the Ambrosia Lake district, but they are less complicated. There, stratigraphically controlled unoxidized prefault ores are distinguishable from unoxidized postfault ores that tend to parallel the strike of faults and probably formed by redistribution of prefault ores. Unoxidized postfault ores have not been recognized in the Laguna district.

On the assumption that the inclined ore rods were vertical when formed, it is postulated that the deposits formed before Late Cretaceous or early Tertiary tilting on the margin of the San Juan (fig. 28). That the main Jackpile ore layers approximately conform to the gentle northwest dip is consistent with this interpretation. If the ore layers formed during or after tilting, they might be more nearly horizontal than the stratification, as they are in the group of deposits at the Sandy mine. (See Hilpert and Moench, 1960, fig. 15.)

In contrast to Cenozoic structural features, those of Jurassic age have localized uranium deposits in many ways. Intraformational folds in Todilto limestone (fig. 36; pl. 9), small penecontemporaneous faults in the Jackpile sandstone (fig. 29), and sandstone pipes all exhibit marked localizing effects. These structures formed during or shortly after accumulation of the units that contain them. In the Sandy mine, uranium deposits are localized mainly along the steep south-facing limb of a Jurassic fold (pl. 8). Because the Todilto limestone is thickest in the structurally low area, this fold probably formed during or shortly after accumulation of the limestone. The uranium deposits form a zone that is more nearly horizontal than the stratification and that crosses from the Entrada, in the structurally high area, to the stratigraphically higher Todilto in the low areas. (See Hilpert and Moench, 1960, fig. 15.) This transection probably means that the deposits are, in part, younger than the folding. The fact that the zone of deposits is also tilted toward the syncline could mean that the deposits formed during folding. Further, the Jackpile deposit is elongate parallel to an inferred Jurassic anticline (pl. 6A), which suggests that this anticline somehow influenced localization of the deposit.

In summary, the geologic evidence appears to bracket uranium deposition to the period between the formation of Jurassic structural features and Late Cretaceous or early Tertiary tilting. Within this interval, all deposits could have formed at the same time or at widely separate times. They could have formed during or shortly after the accumulation of the sediments that contain them, or much later, after deep burial. In our opinion the deposits in the Entrada Sandstone and Todilto Formation formed shortly after Todilto sedimentation, and deposits in the Morrison Formation formed during or shortly after Morrison sedimentation, or at the latest before Dakota sedimentation. This interpretation is consistent with the structural and stratigraphic evidence, and it is likely that the environments for the various processes involved in the formation of the deposits were optimum then.

ORIGIN

The southern San Juan Basin mineral belt was localized by sedimentary and tectonic features that existed or originated when the Late Jurassic host sediments accumulated. At that time a broad east-trending highland existed south of a broad but shallow basin in which continental sediments were being deposited (McKee and others, 1956), and this highland was the major source of sediments in the southern part of the basin. Near the approximate boundary between erosion and accumulation, and perhaps elsewhere, gentle warps formed along axes that were about parallel to the highland. At places these warps localized streams and received unusually thick lenticular accumulations of fluvial sands, as the Jackpile sandstone. Surface and ground waters, of the type outlined by Hostetler and Garrels (1962), flowing from the highland may have extracted uranium and vanadium from the rocks and transported them to the sites of deposition. Such waters might also have extracted soluble humic compounds from surficial or buried decaying plant debris (Vine and others, 1958). These substances may have been precipitated together where the flow was impeded by the prominent stratigraphic and Jurassic tectonic structures that characterize the mineral belt. Impedence of flow might lead to reduced oxygen supply and increased activity of anaerobic sulfate-reducing bacteria; the resulting chemical changes in the ore-bearing ground waters would reduce its capacity to carry uranium, vanadium, and perhaps humic compounds.

SOURCE

Although the source of the major ore components is unknown, we believe that the most logical place is the host sandstones, and perhaps the rocks that were exposed in the broad Jurassic highland in Jurassic time. Both the Entrada and Jackpile sandstones have been partly altered, and both alteration zones can be traced considerable distances south of the mineral belt. Kaolinization of the Jackpile sandstone and stratigraphically lower standstones where they are truncated by the Dakota Sandstone apparently occurred during extensive weathering and erosion prior to Dakota sedimentation. Though we have no supporting evidence, it is conceivable that uranium, vanadium, and other elements were extracted from the rocks during weathering. Alteration of the Entrada Sandstone may also have been an early postsedimentation phenomenon. Preliminary chemical and petrographic data indicate that iron, vanadium, copper, and possibly titanium, silver, lead, zinc, and uranium have been leached from the sandstone (table 2). These data are in approximate accord with those resulting from the more detailed work of Shawe, Archbold, and Simmons (1958, 1959) in the Slick Rock district of Colorado.

The abundant relict volcanic rocks of the Brushy Basin Member of the Morrison should not be overlooked as a possible source of elements. Waters and Granger (1953) suggested that ground waters may have leached alkali metals, uranium, and vanadium from volcanic ash during devitrification. Garrels (1957) suggested that the devitrification of volcanic ash in the presence of ground water will produce optimum solutions for the transportation of uranium and vanadium, and that these solutions will extract uranium from almost any medium they meet. This possibility cannot be tested by petrographic and chemical studies, however, because devitrification apparently destroyed the evidence. The paucity of relict volcanic tuffs stratigraphically near the Entrada Sandstone and Todilto Formation almost precludes this source for elements in deposits of this interval, although the thick bentonitic deposits in the Chinle Formation a short stratigraphic distance below are a possible source.

TRANSPORTATION

Hostetler and Garrels (1962) defined limitations on low-temperature natural solutions capable of transporting abundant uranium and vanadium. Briefly, they reported that the optimum expectable solutions are weakly alkaline and moderately reducing and have an average, or larger than average, concentration of dissolved carbonate minerals. Such a solution is similar to some natural ground waters. Significantly, optimum solutions for the transportation of uranium and vanadium could also carry large amounts of akali-soluble humic compounds, or humic acids (Vine and others, 1958). Although Hostetler and Garrels (1962) considered the problem of uranium-vanadium transport in terms of rather deep subsurface waters, near-surface or surface waters of the type they described are neither unlikely nor uncommon.

Surface and ground waters of this type flowing from the Jurassic Mogollon Highland conceivably extracted uranium and vanadium from the rocks and transported them to the area of the mineral belt. Humic compounds might have been extracted from decaying plant debris in the source area, in the area of the mineral belt, or in the full distance between. In the course of the journey, uranium and vanadium may have been precipitated at places as carnotite by locally more oxidizing conditions (Hostetler and Garrels, 1962), or as uraninite, coffinite, and vanadium clay by locally more reducing conditions, only to be redissolved and carried to a permanent site of precipitation, much as postulated by Gruner (1956b).

PRECIPITATION

Uranium, vanadium, and humic compounds may have been precipitated where ground-water flow was impeded somewhat by the prominent stratigraphic and tectonic structures that characterize the mineral belt. Impedence of flow would induce chemical changes in the ore-bearing solution and reduce its capacity to carry the main ore components. For example, stagnation in areas of impeded ground-water flow might stimulate reduction of sulfate by anaerobic bacteria; the hydrogen sulfide thus generated might effect reduction and precipitation of uranium (Jensen, 1958). In addition, weak acidification by hydrogen sulfide might also cause precipitation of humic compounds, which in turn would tend to extract more uranium from solution. The great affinity of uranium for humic acid is well known (Vine and others, 1958; Szalay, 1954, 1958; Manskaya and others, 1956).

Although impedence of ground-water flow would undeniably reduce the supply of uranium and vanadium to a given site of precipitation, it seems that the problems of precipitation are greater than those of supply per unit time, and that these problems are most easily satisfied by impedence. Complete stagnation would mean that supply had been cut off; but impedence, or reduction of ground-water flow velocity, would result in a favorable environment for precipitation while some supply was maintained. In fact, possibly neither the total ground-water input to the zone of impedence nor the discharge would be reduced at all. Impedence might mean only that a given amount of ground water flowed through a larger volume of sand, and, hence, flowed more slowly; this type of impedence implies some degree of ponding.

The shape of the Jackpile sandstone body (pl. 3; Schlee and Moench, 1961, fig. 3) is ideal for partial ponding and impedence of ground-water flow. All the significant uranium deposits are in the generally thickest part of the sandstone body—hence, in the deepest parts of the Jurassic syncline in which the Jackpile was deposited. In all directions, except northeastward, this unit is unconformably truncated by the Dakota Sandstone; even northeast of the major uranium deposits the unit thins markedly. Thinning to the northeast is expressed in a broad north-northwest-trending zone that may reflect a broad Jurassic anticline that trends about normal to the length of the sandstone body. This means that most of the uranium deposits are in a basinlike depression that formed prior to Dakota deposition. As ground-water flow was probably eastward or northeastward away from the Mogollon Highland, constriction of the sandstone northeast of the main group of uranium deposits would almost certainly have trapped ground water in the depression both before and after Dakota sedimentation. Partial stagnation in an area of many square miles within the depression would have provided an ideal environment for the precipitation of uranium.

If a fairly continuous flow of uranium-bearing water into such a depression is required for the formation of large uranium deposits, mineralization in the district probably predated Dakota sedimentation. After the Dakota was laid down, ground-water recharge of the Jackpile was undoubtedly greatly reduced. The Jackpile sandstone is bounded laterally and below by virtually impermeable mudstones of the Brushy Basin Member of the Morrison, and it is capped by Dakota Sandstone. In the Laguna district the Dakota has low or moderate lateral transmissivity (Jobin, 1962); it is not a good aquifer (Dinwiddie, 1963, p. 217). The thin but extensive black shale strata, particularly where they are at the base of the Dakota, would inhibit the exchange of water between the Dakota and Jackpile sandstone bodies.

If the ores formed shortly after accumulation of the host sediments, as postulated, the prevailing temperature must have been low. No available evidence conclusively indicates that temperatures of ore-bearing solutions were any greater than those of the rocks through which they passed, nor above common average annual surface temperatures in regions having warm climate. Temperatures where the ore was deposited, based on maximum depth of burial in Late Cretaceous or early Tertiary time, are unreliable because of the wide range of possible geothermal gradients (Weeks and Garrels, 1959, p. 8); possibly, however, the ores were not deposited at maximum depths of cover. Temperatures postulated from scant mineralogic evidence (Coleman, 1957) and from the experimental extraction of humic compounds from coal (Breger and Chandler, 1960) for other parts of the Colorado Plateau roughly agree at about 100° ± 45°C. This may only represent the prevailing temperature range at maximum depths of burial. If sulfate-reducing bacteria had a major role in the mineralization (Jensen, 1958, 1963; Jensen and others, 1960), the maximum temperature was probably less than 60°C (Jensen, 1963, p. 185). The suggestion of Abdel-Gawad and Kerr (1961, p. 417) that the coffinite-bearing deposits of the Colorado Plateau formed at temperatures of 200°–360°C is based on the high-temperature laboratory synthesis of coffinite by Fuchs and Hoekstra (1959) and on the presence of coffinite in some vein deposits. The same reasoning can be applied for the formation of pyrite, which is also abundant in some recent sediments. However Abdel-Gawad and Kerr (1961) failed to mention that Fuchs and Hoekstra (1959, p. 1060) believed that coffinite might form in the laboratory at considerably lower temperatures if it were given more time.

Many deposits in the district may have formed below a water table. A water table might account for peculiarities in the distribution of uranium deposits and of unmineralized carbonaceous materials. The Jackpile deposit contains several ore layers that are wholly within the sandstone. A sandstone pipe (pl. 6B) well above the main ore layer in the southern part of the mine contains abundant unmineralized low-rank coal fragments. As some low-rank coal is capable of extracting nearly all uranium from an aqueous solution (Moore, 1954), the coal in the pipe probably would be mineralized if uranium-bearing solutions ever came in contact with it. This relationship might be explained by postulating that a water table extended below the coal and above the main ore body during mineralization. Likewise, the distribution of uranium deposits in the Sandy mine might be explained by postulating that the deposits formed below a water table that crossed the gently folded Entrada-Todilto contact.

Water-table conditions could have prevailed in the zones of the uranium deposits only immediately after sedimentation of the host rocks. Subsequently, the rocks must have remained saturated until recent uplift and erosion. The Entrada Sandstone might have been partly desaturated shortly after the Todilto gypsum evaporites formed, or perhaps when Bluff sedimentation became dominantly eolian. Water-table conditions undoubtedly also existed during accumulation of the fluvial Morrison sands, and also during the possibly long period of erosion that preceded Dakota sedimentation.

Other geologists have recognized the possible role of water tables in the formation of uranium deposits. Fischer, Haff, and Rominger (1947, p. 127) suggested that the vanadium deposits near Placerville, Colo., formed at a slightly uneven water table, or at the contact between ground waters of two types, and definitely before major structual events affected the region. Marks (1958), in his study of ground water in the Gas Hills, Wyo., uranium area, noted that "most above-normal concentrations of uranium occur at local water-table depressions or at water-table terraces where the gradients of the water table flattens." He attributed such concentrations to local impedence of ground-water flow, which permitted reducing agents to precipitate larger amounts of uranium. In the Maybell district, Colorado, Woodmansee (1958) postulated that uraninite and coffinite deposits probably formed originally at and below a paleowater table. As the water table lowered, reduced deposits "stranded" above the water table became oxidized; uranium was leached by downward-moving water and was concentrated along the oxidation boundary some distance above the water table.

Other types of subhorizontal fluid boundaries might have limited the vertical distribution of ores in the Laguna district, but their actions are less plausible. A petroleum-water interface would be subhorizontal and would limit the vertical distribution of any deposits that might form near the boundary. There is no evidence, however, that large quantities of petroleum ever passed through the rocks of the area. The fluid boundary might also have been the contact between two fluids of contrasting salinity. The saline waters that produced the Todilto limestone and gypsum may well have been in contact with fresh waters that flowed into the basin from the southwest. When the Cretaceous sea advanced, sea water undoubtedly encroached on and displaced fresh water contained in the Morrison Formation. As the density of salt water is greater than that of fresh water, the contrasting bodies of water should have been stratified. Density stratification is known to occur on Long Island, N.Y., where pumping has caused the landward movement of salt-water tongues at the base of fresh-water-bearing sand aquifers (Perlmutter and others, 1959; Lusczynski and Swarzenski, 1960). The salt water–fresh water boundaries have gentle landward gradients and are characterized by diffusion zones that range from a few tens of feet to more than 200 feet vertically. The existence of such broad diffusion boundaries in this area of rapid salt-water encroachment—as much as 2,000 feet in 6½ years (Lusczynski and Swarzenski, 1960)—suggests that comparable interfaces in the Jurassic sediments are not likely to have been responsible for the observed vertical distribution of ore. Also, changes in salinity might not have had much effect on the capacity of ground water to carry uranium and vanadium (Hostetler and Garrels, 1962, p. 154, 155). Possible subhorizontal boundaries between ground waters of contrasting temperature are not likely, because there was no evident source of abnormally warm water prior to Tertiary fracturing and igneous activity.

Two lines of evidence against the water-table hypothesis for the Jackpile deposit may be cited, but both are inconclusive. First, the careful observer will note the small mass of ore near the sandstone pipe and about at the level of the unmineralized coalified debris (pl. 8B; fig. 30). Though this indicates that ore-bearing solutions did, in fact, pass through the vicinity of the unmineralized coal, it does not preclude the water-table hypothesis. The small mass could have formed during a brief period of mineralization when the water table rose after the main mineralization; the small amount of uranium (about 10–15 ppm) in the coal could have been acquired during the later stage. Second, the fact that I. A. Breger (written commun., 1959) was unable to extract humic acid from a fragment of coal from the pipe in warm alkaline solutions may mean that soluble humic acids were leached prior to mineralization, and hence, the coal lost its uranium-fixing capacity. Szalay (1958) noted that when humic acids are extracted from peat by an alkaline solution, the peat loses much of its uranium-fixing capacity. On the other hand, most of the coaly materials in the pipe contain resinlike substances for which uranium should have some affinity, because resin is used in milling to extract uranium from solutions.

With the possible exceptions of local barrier effects and possible flowage phenomena (such as ore rods), there is no satisfactory explanation for the boundaries of ore. Boundaries are sharp or gradational, and many cut steeply across sedimentary structures. At places, entire ore layers are in the middle of otherwise homogeneous sandstone, which suggests that ore was precipitated at the interface between contrasting solutions. In the Slick Rock district, Shawe (1956) postulated that ore was precipitated at the boundary between cool connate water and warm ore-bearing water. In the

Laguna district, however, there was no ready source of warm water at the appropriate time.

It is possible that ore was precipitated at the boundary between solutions of contrasting pH and Eh. Consider a model in which uranium- and vanadium-bearing ground waters move slowly through thick alluvial sands. At places the flow of ground water would be impeded by sedimentary structures, abrupt changes in the thickness of the sand, slump structures, and folds. Where impeded, the ground water would become more stagnant, more poorly aerated, and the action of sulfate-reducing bacteria would be enhanced. Hydrogen sulfide thus generated (Jensen, 1958) would render the impeded water more reducing and probably more acidic than the more freely flowing water. Uranium and vanadium would then be precipitated by reduction (Hostetler and Garrels, 1962) at the contacts between the impeded and free-flowing waters. If humic acids also happened to be in the free-flowing ore-bearing solution, they would be precipitated in stagnant water areas by an increase in acidity and would, in turn, tend to extract more uranium from solution (Vine and others, 1958).

The boundaries between such solutions would have various shapes that would partly depend on the direction and velocity of the moving water and the kind of impeding structure. Where the boundaries curve sharply across bedding, roll forms would result; where the position of such curved boundaries fluctuated, banded rolls would result.

Clearly the problems of localization and precipitation of the major ore components are far from being solved. One critical problem concerns the nature of the association of uranium and carbonaceous matter. The humic origin of the carbonaceous matter, though likeliest, has not been established satisfactorily. Further, it is not known whether uranium and carbonaceous matter were transported and precipitated together or separately. It is commonly assumed that carbonaceous matter, whether indigenous or epigenetic, caused the reduction and precipitation of uranium. This idea is plausible because it permits extraction of uranium by carbonaceous matter from very dilute ground waters over long periods of time. On the other hand, it is conceivable that uranium was precipitated first and later extracted carbonaceous matter from ground water by polymerization and dehydrogenation of petroleum or gaseous hydrocarbons (see Charlesby, 1954; Davidson and Bowie, 1951; Pierce and others, 1958; Hoekstra and Fuchs, 1960, for discussions of the processes). We favor the view that uranium, vanadium, and soluble humic compounds were transported in dilute concentrations and were precipitated together.

RESOURCES IN UNEXPLORED GROUND

Because the ore-bearing units in the Laguna district dip generally northwestward, uranium deposits are exposed at the surface only in one outcrop belt. Northward and northwestward the Jurassic ore-bearing units are buried by Cretaceous strata to depths of several thousand feet below Mesa Chivato and Mount Taylor. We suspect that the southern San Juan Basin mineral belt extends northwestward beneath the Mount Taylor volcanic field and the McCarty's syncline to the Ambrosia Lake district, but there excessive depths will prohibit prospecting for many years. East of the north-trending San Ignacio faulted monocline on the east side of the district, the ore-bearing beds are buried beneath thick Cretaceous and Tertiary strata in the Rio Grande depression. Again excessive depths, combined with complex structure, will prohibit immediate prospecting. Also, it is not likely that large deposits exist in units other than the Jackpile sandstone. However, prospectors should not overlook the possibility that uranium deposits may be found on the eastward projection of the mineral belt in Jurassic rocks east of the Rio Grande depression and the Sandia-Manzano Mountains.

Areas to the north and south of the known limits of the mineral belt are not generally favorable for prospecting. To the south the ore-bearing units wedge out on depositional and erosional edges on the north flank of the Jurassic Mogollon Highland. The northern side of the mineral belt, 10–15 miles north of the Jackpile mine, has been prospected, and a few small deposits have been found. The Jackpile sandstone extends northeastward toward the Nacimiento Mountains and may contain deposits well northeast of any known occurrence. If the mineral belt is genetically related to the south margin of Jurassic sedimentation on the flank of the Mogollon Highland, as we believe, significant deposits probably will not be found much beyond the present northern limit of the mineral belt.

We believe that the most major deposits will be found in a west-northwest-trending zone about 10 miles wide that is centered at the Jackpile mine. The most favorable area for prospecting in the Jackpile sandstone is probably west of the Paguate deposit, along the projection of the Paguate–Saint Anthony group of deposits. The north and south margins and the northeast end of this belt have been defined by drilling and surface exposures. Excessive depth of the ore-bearing unit farther west has inhibited sufficiently close-spaced drilling there to define ore bodies.

Because the Westwater Canyon Member of the Morrison is the major ore-bearing unit in the Ambrosia Lake district, and because it contains a few small deposits on the east side of Mesa Gigante, it may have ore-bearing potential in the Laguna district. If so, the area of likely ore occurrences in the Laguna district is considerably enlarged. The Westwater Canyon, as well as other sandstone units in the Morrison Formation, may be thickest in the broad Jurassic syncline that localized the Jackpile sandstone. In the northeast corner of the Laguna district the Westwater Canyon Member is exceptionally thick but not strongly mineralized. As the Jackpile sandstone contains only small deposits here, so may the Westwater Canyon, possibly because of its distance from the Mogollon Highland. Southwestward toward the Jackpile mine, and then west-northwestward toward the Ambrosia Lake district, the Westwater Canyon Member may contain significant deposits.

The best prospecting procedure in these areas, we believe, would be first to drill through the Morrison Formation on 1-mile centers in an area slightly broader than that of the Jackpile sandstone. This likely would outline the thickest parts of the Westwater Canyon and possibly disclose the shape of the unit. With the target thus delimited, closer spaced drilling on 1,000-foot or closer centers could then be concentrated in the thickest parts of the unit. Because deposits rarely exceed 1,000 feet in width, though they may be several thousand feet long, wider spaced drilling might easily miss a large deposit. We recognize, however, that the present economics of exploration are not amenable to such deep drilling. If the economics of deep exploration and mining improve sufficiently, the whole area between the Jackpile mine and the Ambrosia Lake district may be considered favorable ground, and the Westwater Canyon Member as well as the Jackpile sandstone should be prospected.

Future exploration, in our opinion, should be consistent with the concept of the southern San Juan Basin mineral belt. Within the mineral belt the geometry or shape of the potential host units, particularly the Westwater Canyon Member of the Morrison, should be marked out before detailed prospecting for ore deposits is attempted. We believe that the ores probably formed shortly after sedimentation of the rocks that contain them, or at least before deep burial, and that the mineral belt was controlled by near-surface conditions that prevailed in a limited zone along the north margin of the Mogollon Highland and the south margin of Jurassic sedimentation. If this is true, as is indicated by paleogeographic maps by McKee and others (1956), uranium deposits may well be found east of the Rio Grande on the approximate projection of the mineral belt, as well as west or northwest of the Laguna district, provided favorable host rocks are present there. Such rocks include deformed limestone of the Todilto Formation and fluvial deposits of the Morrison Formation.

In summary, paleogeographic maps probably provide the best guides to the discovery of uranium districts. In our opinion the most favorable regions are those in which sediments were shed from a broad area of weathered granitic rocks, acidic volcanic rocks, or immature clastic sedimentary rocks into an adjacent shallow basin of dominantly fluvial sedimentation. In addition, the permeable sediments near the margins of the basin should be characterized by many thickness changes and, perhaps, by many subtle structural features. These features would impede the flow of ground waters, change their character from weakly oxidizing or moderately reducing to strongly reducing and from weakly alkaline to weakly acid, and provide the conditions under which uranium, humic acids, and other ore components could precipitate.

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