TEI-510

URANIUM DEPOSITS OF THE SOUTHERN PART OF THE SAN JUAN BASIN, NEW MEXICO

By L. S. Hilpert and R. H. Moench

Trace Elements Investigations Report 510

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

IN REPLY REFER TO:

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON 25, D.C. October 21, 1959

AEC - 329/9

Mr. Robert D. Nininger
Assistant Director for Exploration
Division of Raw Materials
U. S. Atomic Energy Commission
Washington 25, D. C

Dear Bob:

Transmitted herewith are three copies of TEI-510, "Uranium deposits of the southern part of the San Juan Basin, New Mexico," by L. S. Hilpert and R. H. Moench, March 1959.

We plan to submit this report for publication in Economic Geology.

Sincerely yours,

for Montis R. Klepper
Assistant Chief Geologist

TEI-510

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

URANIUM DEPOSITS OF THE SOUTHERN PART OF THE SAN JUAN BASIN, NEW MEXICO*

By

L. S. Hilpert and R. H. Moench

March 1959

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*This report concerns work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

USGS - TEI-510

GEOLOGY AND MINERALOGY

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URANIUM DEPOSITS OF THE SOUTHERN PART OF THE SAN JUAN BASIN, NEW MEXICO

By L. S. Hilpert and R. H. Moench

ABSTRACT

Since 1950 about 50 million tons of uranium ore has been discovered along the southern margin of the San Juan Basin, New Mexico. Here the exposed sequence of sedimentary rocks ranges in age from Permian to Cretaceous, and this sequence is associated with intrusive and extrusive rocks of Tertiary and Quaternary age. The uranium deposits of the region group themselves into three types--those in sandstones and associated mudstones of the Entrada and Morrison formations of Jurassic age and Dakota sandstone of Cretaceous age; those in the Todilto limestone of Jurassic age; and one deposit in a pipelike structure in the Morrison formation. The deposits in the clastic sediments are similar to most of the uranium deposits in other parts of the Colorado Plateau region in type and habit of ore and accessory minerals, in the tabular form of ore bodies, and in their association with some form of carbonaceous material. The deposits in limestone have a somewhat similar mineral assemblage to that of the other deposits in the region but are unique in the type of host rock and their preference for structurally deformed beds. The pipelike deposit is unique.

Although igneous activity has been intense in the eastern part of the area from late Tertiary to Recent time, there is no evidence to suggest a genetic relationship between the igneous activity and the

uranium deposits. In fact, what are probably the oldest exposed igneous rocks intrude and displace the deposits.

Three periods of deformation are recognized. The first was during the period between the accumulation of the Entrada and Dakota formations, the second in the early to middle Tertiary, and the third in the middle to late Tertiary. Only structures of the first period show an obvious influence on the distribution and localization of the uranium deposits. From the pattern or frequency of distribution of the known deposits, and on the basis of interpretations from known geologic relations, it appears that the deposits are clustered in a zone at least 20 miles wide behind the present outcrop; this idea permits the concept of the southern San Juan Basin mineral belt. Although this concept restricts the favorable ground geographically, the amount of unexplored ground within the limits of this belt is enough to contain several times as much uranium resources as are now known.

INTRODUCTION

The discovery, in 1950, of a uranium deposit along the southern margin of the San Juan Basin in northwestern New Mexico prompted intensive exploration that already has found about 50 million tons of ore reserves, classed as available, and worth at least a billion dollars at the current (1958) price schedule. The known deposits are in an area about 20 miles wide extending from Gallup to Laguna, a distance of about 85 miles (fig. 1). The name "southern San Juan Basin mineral belt" is suggested for this area.

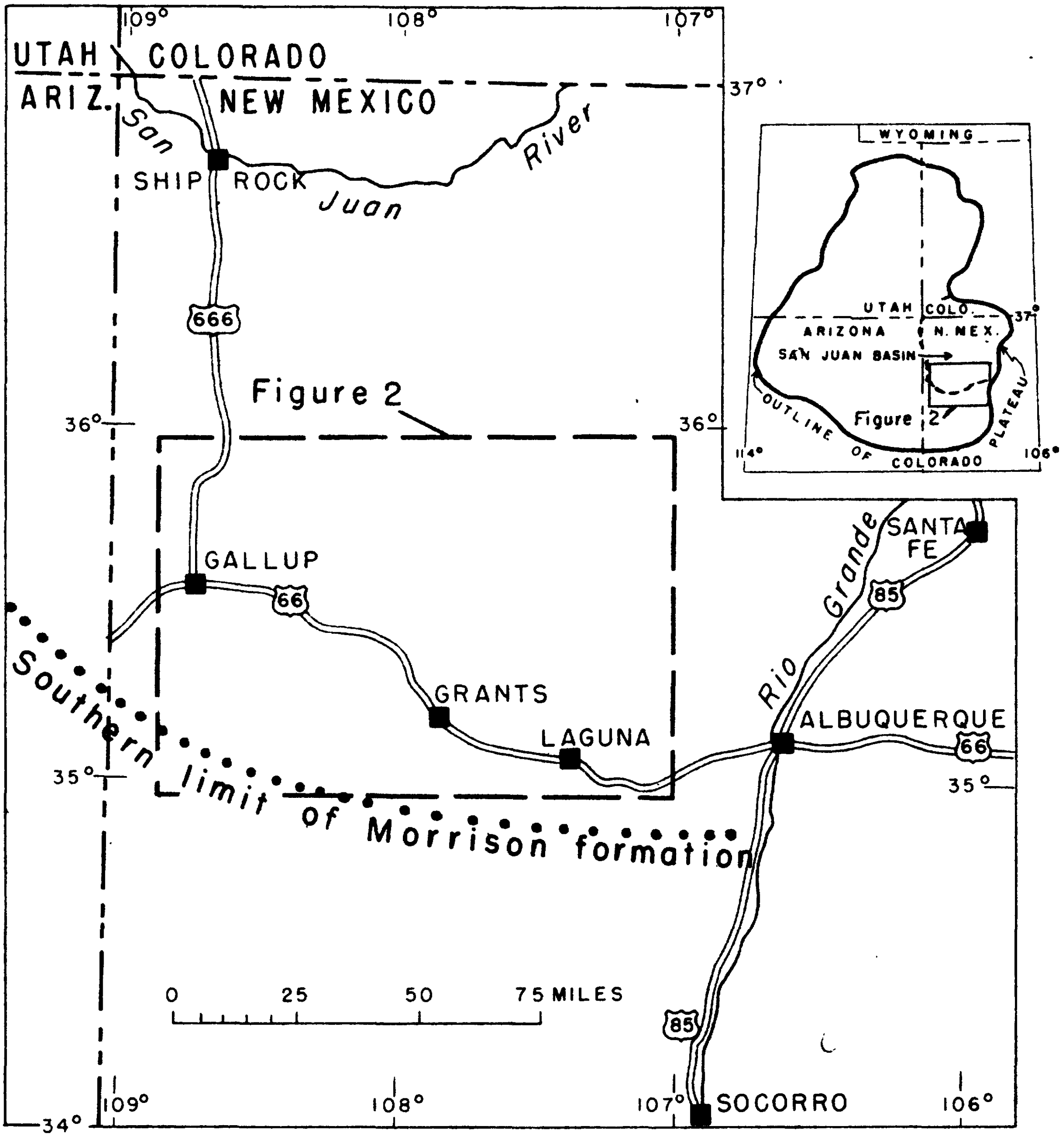

Figure 1.--Index map of northwestern New Mexico.

This paper briefly summarizes the general geologic relations of these deposits, speculates on the origin and localization of some individual deposits and the entire belt, and attempts to appraise the chances for additional discoveries. Although some new evidence and interpretations are presented, space does not permit a detailed description of the deposits and the inclusion of all evidence to support the interpretations. This paper was originally prepared for publication in the Proceedings of the United Nations' Second International Conference on the Peaceful Uses of Atomic Energy. For lack of space the original paper had to be drastically cut, leaving out much material that was essential. The paper, essentially as originally written, is presented here to give a more complete description of the geologic relations and to reach those readers that might not have ready access to the Proceedings of the Second International Conference.

This presentation is based largely on the results of areal and mine mapping that was done in the Laguna district (fig. 2) by R. H. Moench and associates between July 1955 and May 1958, and on regional reconnaissance and specialized studies by L. S. Hilpert and associates between July 1954 and May 1958.

GENERAL GEOLOGY

The San Juan Basin is a structural unit covering an area of about 15,000 square miles in northwestern New Mexico (fig. 1). Rocks exposed along the southern margin consist of sedimentary strata ranging in age from Permian to Cretaceous inclusive, and associated with intrusive and extrusive rocks of Tertiary and Quaternary ages. The sedimentary rocks generally dip northward at low angles toward the center of the basin, but this regional attitude is modified locally by faults and minor folds.

STRATIGRAPHY

All productive uranium deposits along the southern margin of the San Juan Basin are in sedimentary rocks of Jurassic and Cretaceous age. The lithologic characteristics and variations in thickness of these strata and the stratigraphic distribution of the uranium deposits are summarized in table 1. More detailed descriptions of the Todilto limestone and the Morrison formation, both of Jurassic age, are given below, for these two formations contain most of the deposits in the region.

The Todilto limestone is gray and has a fetid odor when freshly broken. Except where coarsely recrystallized, it is fine-grained and thinly bedded in the lower part and medium-grained and massive in the upper part.

In the central and eastern parts of the southern San Juan Basin mineral belt, where the Todilto limestone is ore-bearing (fig. 2), the Todilto averages about 20 feet thick, but it ranges considerably in thickness locally. In many places the limestone beds are conspicuously deformed by folding and faulting; most of this deformation is entirely within the formation, but in some places a few feet of beds above and below the formational contacts are disturbed, thus causing abrupt though small changes in the thickness of the formation. In the Laguna district the Todilto is several feet thinner than average on the crests of broad small amplitude folds of Jurassic age and correspondingly thicker than average in the troughs of these folds.

The Todilto limestone pinches out southward along a line about 12 miles south of Laguna and 15 to 20 miles south of Grants, and it pinches out westward along a north-trending line several miles east of Gallup. The formation is as much as 85 feet thick in the northern part of the Laguna district, where the upper part of the formation is composed of anhydrite and gypsum.

Except where it is strongly deformed and recrystallized, the Todilto limestone in the Ambrosia Lake district can be separated into three stratigraphic zones; from bottom to top these are commonly referred to by the miners as the "platy," "crinkly," and "massive" zones. The lower two zones are about equal in thickness and constitute about half the total thickness of the formation. The "platy" and "crinkly" zones consist of fine-grained, thin-bedded limestone with thin partings of siltstone; black, dense, carbonaceous material is conspicuous locally along the partings in the "crinkly" zone. The bedding in the "platy" zone is generally undisturbed, whereas, that in the "crinkly" zone is intensely crenulated. The "massive" zone consists of more coarsely crystalline limestone with indistinct bedding. In many places this zone is a breccia of limestone fragments, mostly cemented by calcite. Locally the top of the "massive" zone is a breccia, with fragments of limestone embedded in sand derived from the overlying Summerville formation. The upper part of this zone also contains lenses of siltstone, indicating a gradational contact with the Summerville. In the Laguna district the part of the Todilto below the "massive" zone contains a sequence of beds that have characteristics of both the "crinkly" and "platy" zones, but are not separable into these two units as they are in the Ambrosia Lake district.

Uranium deposits occur in all three stratigraphic zones in the Todilto. Probably most deposits are in the "platy" or "crinkly" zones, but they may occur in any one or in any combination of the three zones. The deposits are all localized where the limestone beds are deformed by folding and faulting, most of which is entirely intraformational.

The Morrison formation ranges from less than 100 to as much as 600 feet in thickness in the area of the southern San Juan Basin mineral belt. This formation extends over a broad region to the north, northwest, and northeast of this area, but a short distance south of the area the Morrison has been removed by pre-Dakota erosion. Here the Dakota sandstone rests unconformably on progressively older beds south of the mineral belt area.

The Morrison comprises three members--the Recapture, Westwater Canyon, and Brushy Basin members--that have partly ill-defined or gradational contacts. The Recapture member is the lowest, and it consists dominantly of sandstone with some silty claystone beds. The sandstone is fine- to medium-grained and forms alternating light-gray and reddish-brown units 5 to 10 feet thick. The Recapture member is absent locally in the Laguna district, but it is as much as 170 feet thick elsewhere in the mineral belt area (fig. 3).

In some places along the southern margin of the San Juan Basin the Westwater Canyon member--the middle unit of the Morrison formation--has not been separated from the overlying Brushy Basin member except arbitrarily. Both contain beds of similar lithologic types but in different proportions. The Westwater Canyon member is composed dominantly of light-colored fine- to coarse-grained arkosic sandstone, with some

Brushy Basin-type claystone. The Brushy Basin member is composed dominantly of greenish-gray claystone, with some Westwater Canyon-type sandstone. In this report the contact between these two members is arbitrarily placed at the base of the lowest layer of Brushy Basin-type claystone that is fairly thick and continuous. Where a layer of claystone that projects into Westwater Canyon-type sandstone pinches out, as shown on the left side of figure 3, the contact of these two members is lowered or raised to the base of another layer of Brushy Basin-type claystone. Thus the so-called "Poison Canyon" sandstone, which is of the Westwater Canyon-type, lithologically, is placed in the lower part of the Brushy Basin member (fig. 3).

With this approach, the Westwater Canyon member is conceived as thinning eastward from a thickness of 300 feet near Gallup to discontinuous lenses near Laguna. The Brushy Basin member, on the other hand, ranges from 0 feet near Gallup to about 500 feet north of Laguna.

As presently used, the "Jackpile" sandstone, which is exposed only in the Laguna district, is included in the Brushy Basin member. It forms the uppermost part of the member, and ranges up to 190 feet in thickness. According to J. S. Schlee (14, p. 1793, and oral communication) the "Jackpile" sandstone is a fluvial "shoestring" sand about 10 miles broad with distributary-like channels to the northeast. The unit trends northeasterly across the Laguna district, and sedimentary structures indicate that these fluvial sands were transported northeasterly, parallel to the length of the unit.

The important ore-bearing sandstones are generally in thick layers, with crossbedding dominantly of the fluvial type, and they are intercalated with relatively thin and discontinuous lenses of claystone. The sandstones are mostly fine to medium-grained, but are locally conglomeratic, and they are dominantly feldspathic. The Westwater Canyon-type sandstones, and the lower parts of the "Jackpile" sandstone are cemented by silica, calcite, and lesser amounts of clay, but the upper part of the "Jackpile" sandstone is mostly clay-cemented. Fragments of fossil tree trunks and limbs are also present in the sandstones; they are commonly silicified, but some are coalified. A fine-grained black carbonaceous material that is uranium-bearing is abundant in the uranium deposits; it impregnates the sandstone, and probably was introduced after the sands accumulated (<u>see</u> Deposits in clastic sediments).

The sandstones of the Westwater Canyon and Brushy Basin members except the "Jackpile," are typically yellowish gray to light grayish red, but near ore deposits they have been altered to light gray. The "Jackpile" sandstone, on the other hand, is dominantly light gray to nearly white; its lighter color probably resulted from weathering before the overlying Dakota sandstone was deposited. The "Jackpile" and other beds in the upper part of the Brushy Basin were truncated by erosion before the Dakota accumulated.

Electric log data from the few holes that have been drilled north of the Ambrosia Lake district suggest that the sandstone of the Westwater Canyon member there is more uniform in thickness and character, and contains less mudstone than in the mining district. This difference may indicate a northward change to more uniform conditions of sedimentation.

As the host sandstones of the Morrison formation in the mining district are characteristically variable in texture and composition, this possible change of sedimentation conditions may have produced a rock that is less favorable for the localization of ore.

Nearly all the known uranium deposits in the Morrison formation in the mineral belt area are in sandstone beds in the "Jackpile" and Westwater Canyon sandstones. The Westwater Canyon member contains the largest deposits in the Ambrosia Lake district and moderate-sized deposits in the Gallup district. Some deposits in the Ambrosia Lake district are in the lower part of the Brushy Basin member, whereas those in the Laguna district are in the "Jackpile" sandstone near the top of the unit.

Deposits in the Ambrosia Lake district are distributed mainly in two elongate groups--the Ambrosia trend, containing the largest deposits in the district, and the Poison Canyon trend (fig. 4). In figure 5, section A-A', drawn north-south across the Ambrosia trend, the bulk of the deposits are grouped near the central part of a thick sandstone mass. This sandstone mass perceptibly thins and tongues into the Brushy Basin mudstones both north and south of the group of deposits. On the other hand, in sections B-B' and C-C', which are longitudinal to the Ambrosia trend, the sandstone mass appears to be more uniform in thickness and in lithologic continuity than in section A-A', except over the Ambrosia dome. These relations suggest that the deposits of the Ambrosia trend are in the central, relatively thick part of a sandstone mass that is elongated in an easterly to southeasterly direction, and that this elongate mass of sandstone is responsible for the belt-like grouping of the deposits.

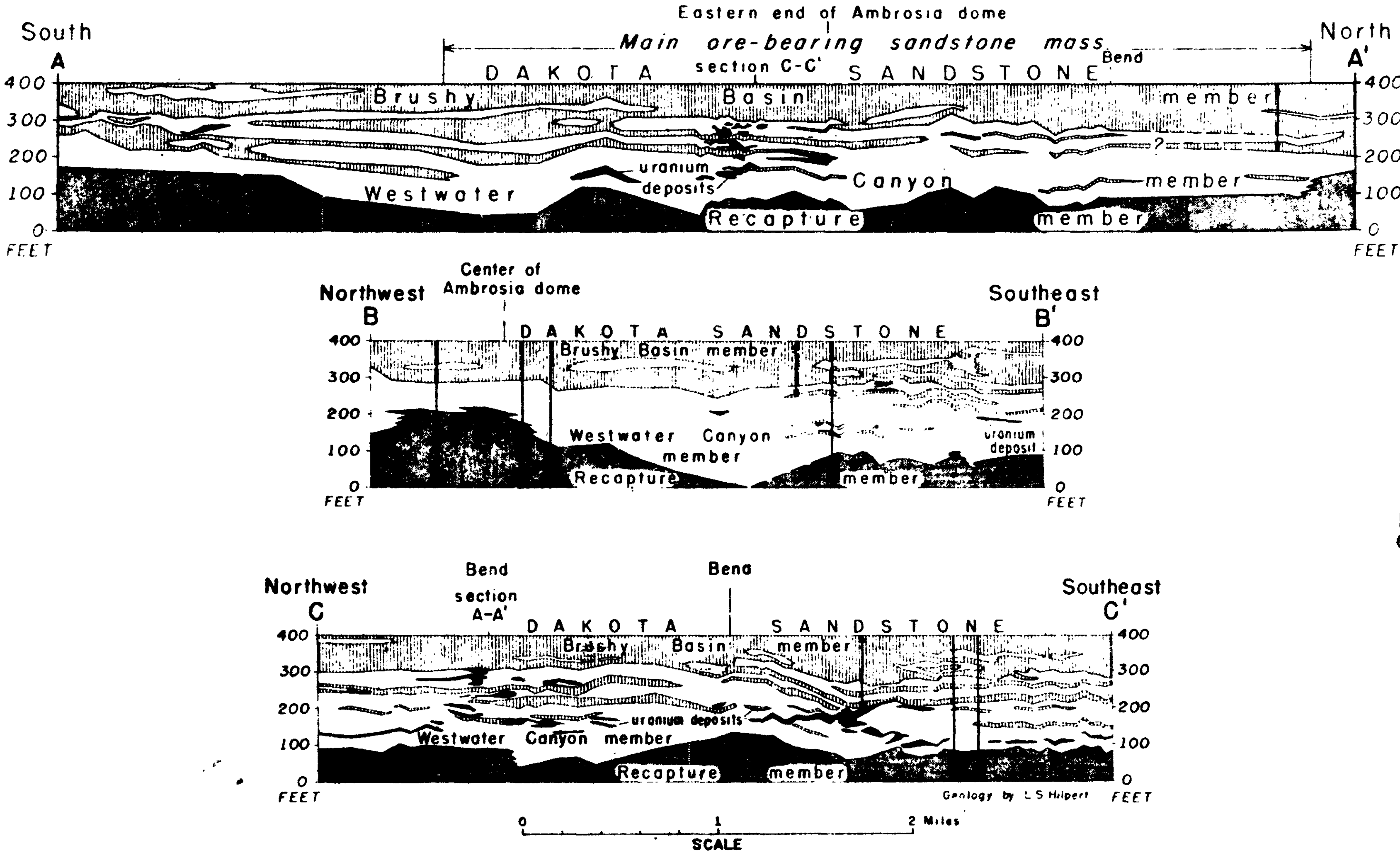

Figure 5.--Geologic sections of the Morrison formation in the Ambrosia Lake district showing the relations of the uranium deposits to the stratigraphic units and to the Ambrosia dome; post-Dakota folds removed.

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Likewise, the deposits of the Poison Canyon trend appear to be localized in the central part of an east-trending sandstone unit (7,8,2,3; Mathewson, D. E., written communication, 1953).

In the Laguna district the deposits in the "Jackpile" sandstone are not distributed in as clearly defined belts, and the Jackpile uranium deposit is elongated about at right angles to the dominant northeasterly sedimentary trends. The known deposits, however, are grouped in a broad zone near the central and thickest parts of the "Jackpile" sandstone.

STRUCTURAL GEOLOGY

The sedimentary strata along the southern margin of the San Juan Basin generally dip northward at low angles, but they are broken by faults, joints, and warped by gentle folds; and some units are deformed locally by intraformational folds, faults, and collapse structures. Although some individual structural features cannot be dated with complete confidence, three general periods of deformation are recognized since the accumulation of the Entrada sandstone, the oldest formation of Jurassic age in the area. The first period was during Jurassic time, the second in the early to middle Tertiary, and the third during middle to late Tertiary.. Only structures of the first period show an obvious influence on the distribution and localization of the uranium deposits.

The first period of deformation--during Jurassic time and possibly extending into early Cretaceous time--produced two sets of folds and probably the smaller structures that appear to be associated with them.

Figure 6 illustrates the distribution of these folds and smaller structures in the Laguna district. Here one set of folds consists of broad, gentle warps that generally trend easterly, but are sinuous. The largest of these warps is perhaps several miles wide, with an amplitude of a few hundred feet. In the Laguna district this set of easterly trending warps contains the largest folds of the Jurassic fold system and is termed the major set. This set is essentially parallel to the northern margin of a broad highland that existed in central and southern New Mexico in Jurassic time (13).

A similar set of folds probably also exists in the Ambrosia Lake district. In figure 7, section D-D', drawn north-south between the Poison Canyon and Ambrosia trends (see figure 4), a set of broad folds is expressed by the sandstone and claystone layers of the Morrison formation, which in turn is unconformably overlain by the Dakota sandstone. In section E-E', drawn east-west in the same area, the Dakota sandstone appears to conformably overlie the Morrison formation, and no pre-Dakota folds are apparent. Section E-E', therefore, is essentially parallel to a set of easterly-trending pre-Dakota folds, and section D-D' is normal to this set of folds. In addition the sandstone and claystone layering in the Morrison appears to be more uniform and continuous in an easterly direction, parallel to the trend of the folds (section E-E') than in a northerly direction (section D-D'), a relation similar to that expressed by the Westwater Canyon sandstone mass in the vicinity of the Ambrosia trend.

The Ambrosia dome (fig. 4) is a prominent structure that involves the Dakota and younger rocks, and is, therefore, in part a younger structure. In figure 5, section B-B', however, the Westwater Canyon member thins markedly over the crest of the dome, and is relatively thick around the entire periphery of the dome. It is doubtful that the thinning of the Westwater Canyon member over the dome resulted from differential compaction because the Brushy Basin claystone shows no similar thinning over the crest of the dome. It seems more likely, therefore, that the dome was a positive or relatively high domal feature in Morrison times, receiving less sand over its crest than around its periphery.

The second set of Jurassic folds is well developed in the Laguna district (fig. 6). Most are about a half a mile across, with amplitudes of as much as 100 feet, and they trend persistently N.10°-30°W. They are much smaller than the largest folds of the easterly-trending set and are termed the minor set of the Jurassic fold system. For lack of exposure the intersections between folds of this set and the easterly-trending set were not seen, but both sets of folds may occur in the same areas.

The bedding of the Todilto limestone is contorted in many places in the area. Where strongly disturbed, the beds are folded into a great variety of shapes--as open and closed anticlines, fan folds, recumbent folds, and chevron folds, most of which are asymmetric. Although parts of the folds are fractured, and some folds are cut by small low-angle thrust faults, the characteristics of plastic deformation are dominant. The amplitude of these structures is about equal to, or somewhat less than, their breadth, which ranges from less than an inch to about 30 feet.

Although some of the largest folds involve beds in the top few feet of the underlying Entrada sandstone and basal beds of the overlying Summerville formation, most of the folds are confined to the Todilto limestone. At least in the Laguna district these folds in the Todilto limestone are localized mainly along the flanks and troughs of the broad east-trending and north-trending folds, and their dominant trends are likewise eastward and northward, as indicated by the rose compass diagram in figure 6. Northward and eastward are also the dominant trends of the folds in the Todilto limestone in the Ambrosia district, but their relations to the broad pre-Dakota folds has not been determined. As the Todilto limestone in the Laguna district is somewhat thicker in the troughs of the broad folds than on the crests, these data combined suggest that the intraformational folds developed by flowage of poorly consolidated muds down the limbs of the broad folds. This flowage occurred under some sedimentary cover in post-Todilto time because none of the folds is truncated by bedding planes.

Peculiar collapse structures are common in the Morrison formation and in the Bluff and Summerville formations in the area. They are circular in plan and vertical in orientation, and they range from 1 inch to 200 feet in diameter and from 1 foot to 300 feet high. Locally they are called "sandstone pipes" or "breccia pipes." One of the several hundred pipes found in the area is known to contain uranium ore, that at the Woodrow mine (see figure 14 and section titled the Woodrow deposit). Subsequent to the preparation of this report the pipe that is exposed in the Jackpile mine has been found to be mineralized to some extent (see figures 8 and 9).

Typically the pipes are bounded by a ring fault, or by several concentric ring faults and the beds surrounding the pipes are commonly inwardly downwarped (figs. 8, 9, and 14). The material at any point in a pipe consists of the same material that forms the wall rock a short distance above, but it has been largely disaggregated and shows little or no bedding or other sedimentary structure. The pipe-filling material is compact and without voids other than the pores of the rock. The pipes flare upward and are covered by undisturbed beds. Downward, though their bases are rarely seen, they likewise pass into undisturbed beds. Typically the pipes terminate at their tops in sandstone, and extend downward into mudstone or siltstone. The pipes are largely confined to two stratigraphic units--the Morrison formation, and the lower part of the Bluff sandstone downward into the Summerville formation. None is known to penetrate the Todilto limestone or the Dakota sandstone. Their general stratigraphic range, therefore, is about 1,000 feet.

The tops of some pipes are well exposed and provide a basis for determining their time of origin. Figure 8 is a section through the top of a pipe in the "Jackpile" sandstone. The general characteristics of this pipe are similar to those described above, but in particular it illustrates the upward flare of the top, and the fact that it both cuts and is overlain by "Jackpile" sandstone. In addition this pipe contains abundant and diverse types of fragmental carbonaceous material, whereas the wall rocks are essentially barren of carbonaceous material. The authors interpret that this pipe formed during the deposition of the "Jackpile" sandstone, and was buried by additional "Jackpile" sandstone. It probably formed rapidly, sucking into it much plant debris from its immediate surroundings at the surface. The plant debris probably was thus buried and preserved, whereas, in the wall rocks it was not. Other pipes reveal unconformable relations between the downwarped sandstone at their tops and the overlying undisturbed sandstone, indicating that they formed at the time of sedimentation of the units that contain them.

From the observations made so far, no satisfactory interpretation can be offered to explain the origin of these collapse features. They evidently formed during the accumulation of the highest beds they cut, and before complete compaction and consolidation of the beds containing them. Most of the pipes in the Laguna district are localized in long narrow belts that closely parallel the Jurassic folds of both sets (fig. 6), suggesting that this deformation influenced the collapse in some way.

The Jurassic folds of both the easterly- and northerly-trending sets formed prior to the deposition of the Dakota sandstone, and possibly contemporaneously with the deposition of the Jurassic rocks above the Entrada sandstone. Folded rocks in both the Laguna and Ambrosia Lake districts are truncated in many places by the overlying Dakota sandstone, demonstrating the pre-Dakota age of the folds. As the sandstone pipes originated during the deposition of the Summerville, Bluff and Morrison rocks, and are commonly localized in belts that closely parallel the folds, it is likely that the folds developed in part at the same time. In addition, as the intraformational folds in the Todilto limestone probably resulted from flowage of poorly consolidated lime down the flanks of the broad folds, it is likely that the broad folds developed in part not long after Todilto deposition.

If the Jurassic folds developed contemporaneously with the deposition of the Jurassic rocks, more likely than not the folds influenced the deposition and distribution of these rocks. The sandstones of the Morrison formation in both Laguna and Ambrosia Lake districts are interpreted to have been thus influenced. The "Jackpile" sandstone, in the shape of a "shoestring" sand, roughly parallels the major easterly-trending set of Jurassic folds; the data on cross-lamination suggest that the sands were transported in the same direction (fig. 6). In addition, the thickness of the Morrison formation beneath the "Jackpile" sandstone increases by as much as 150 feet from the margin of the "shoestring" to its center. It is possible, therefore, that in the vicinity of the "shoestring" sand the Morrison formation occupies a broad northeast-trending warp that formed contemporaneously with the deposition of the Morrison, and that the stream that deposited the "Jackpile" sandstone was controlled by this warp.

In the Ambrosia Lake district pre-Dakota folding may have likewise influenced the deposition of the Morrison formation. It has been noted previously that the sandstone and mudstone layering are most continuous and uniform in thickness in an easterly direction, which is essentially parallel to the elongation of the sandstone host of the Ambrosia trend. It has also been noted that at least one set of pre-Dakota folds in this district has an easterly axial trend. It is possible, therefore, that broad gentle folding during Morrison time tended to localize into easterly courses the streams that deposited the sandstones.

The second period of deformation was in early to middle Tertiary time. Uplift again occurred in the area of the Zuni Mountains and subsidence in the area of the San Juan Basin defined this structure. The movements tilted the beds into low-angle northerly to northeasterly dips west of the Mount Taylor area and northerly to northwesterly dips on the east side. The McCartys syncline, which marks the change in these dominant dip directions, also formed at this time, as well as the faults and folds near the eastern end of the Zuni uplift. The Ambrosia dome, which probably started to form before the Dakota formation was deposited, became well defined. The faulted monocline that marks the western boundary of the Rio Grande trough (fig. 2) may also have formed at this time.

The third period of deformation took place during middle to late Tertiary, and possibly into Quaternary times, when the Colorado Plateau province was uplifted regionally and the Rio Grande trough subsided. In the region of the southern San Juan Basin mineral belt this deformation was characterized dominantly by fracturing. To a limited extent fracturing took place during the two earlier deformations, but as middle to late Tertiary was the time of greatest differential movement between the Rio Grande trough and the Colorado Plateau, this was probably the time of most intense fracturing in the mining districts. The joint and fault system in the Laguna district is similar to that on the western edge of the Rio Grande trough, and the late Tertiary and Quaternary igneous rocks are fractured by the same system.

Although some geologists believe that the fractures of post-Dakota age influenced the localization of the uranium deposits along the southern margin of the San Juan Basin--and certainly these fractures had some influence on the distribution of secondary minerals--the writers believe that these structures formed later than the primary mineralization. Where post-Dakota faults intersect ore deposits they cut and displace the ore. Some fractures carry ore minerals of uranium and vanadium, but only where the fractures cut ore deposits, and where such deposits show obvious effects of oxidation. Furthermore, where the distribution and trend of deposits show a suggested parallelism or association to fracture systems, the occurrences invariably seem to be above the present water table where there has certainly been some oxidation and redistribution of uranium.

RELATIONS OF URANIUM DEPOSITS TO IGNEOUS ROCKS

Igneous activity has been intense in the eastern part of the Gallup-Laguna area from late Tertiary to Recent times. It probably began with the intrusion of diabasic sills and dikes, followed by the formation of Mount Taylor, a large stratified volcano, and closely followed by sporadic outpouring of basaltic lava from a great many pipes and fissure vents in the immediate vicinity of Mount Taylor.

Diabasic sills and dikes east of Mount Taylor interconnect and probably were intruded contemporaneously, though this intrusion is not accurately dated. The dikes dominantly follow the prominent north-trending fracture set, and the sills, in turn, are jointed and locally faulted by the same set. This suggests that the diabase was intruded contemporaneously with fracturing that formed mostly in middle to late Tertiary time. Inclusions of the diabase were found in a volcanic pipe that probably supplied one of the earliest basaltic flows, indicating that the diabasic rocks are at least older than what may be the oldest basaltic flows. These basaltic flows were extruded essentially contemporaneously with the latest stages of the Mount Taylor eruptions. Because the entire Mount Taylor sequence probably formed over a short period of time, the authors suspect that the diabasic intrusions took place before both the basaltic and Mount Taylor extrusions.

The volcanic rocks of Mount Taylor consist dominantly of pyroclastics and flows of rhyolite, trachyte, and latite, and also dikes of prophyritic andesite (9). The basaltic flows, pipes, and fissure vents in the immediate vicinity are composed dominantly of olivine basalt, but include some rocks of intermediate composition. Both the Mount Taylor stratovolcano and the oldest basaltic flows rest on an erosion surface that is probably younger than the major structural developments in the Rio Grande trough. The oldest basaltic flows are probably overlain by some of the pyroclastics from Mount Taylor, and overlying basaltic flows intertongue with an alluvial cone built out from the upper part of Mount Taylor; these relations suggest little, if any, break in time between the Mount Taylor eruptions and the extrusion of the basaltic flows. Younger basaltic flows rest on younger erosion surfaces, and some flows follow the present drainage.

The distribution pattern of the known deposits in the entire mineral belt area does not suggest a spatial relationship to the igneous rocks (fig. 2). Furthermore, the diabasic dikes and sills, probably the oldest igneous rocks, intrude and displace many uranium deposits in the

Laguna district (fig. 11 and 17) and metamorphose them along the contacts. As these rocks are younger than the deposits, it is unlikely that they influenced the localization or origin of them.

URANIUM DEPOSITS

The uranium deposits along the southern margin of the San Juan Basin group themselves into three types--those in sandstones and associated mudstones of the Entrada, Morrison, and Dakota formations; those in the Todilto limestone; and one deposit in a pipelike structure. The deposits in the clastic sediments are similar to most of the uranium deposits in other parts of the Colorado Plateau region in type and habit of ore and accessory minerals, in the tabular form of ore bodies, and in their association with some form of carbonaceous material. The deposits in limestone have a somewhat similar mineral assemblage to the other deposits in the region but are essentially unique in the type of host rock and their preference for structurally deformed beds. The pipelike deposit is truly unique in the area, though similar in some respects to the deposit in the collapse structure at Temple Mountain, Utah, and perhaps a few other occurrences in down-faulted rocks.

In spite of the differences in stratigraphic position and the lithologic and structural environments of the deposits in the southern part of the San Juan Basin, the writers believe that they all belong to the same general class and had a common origin. The geologic relations that are a basis for this idea, and certain other geologic relations that will be described, permit the concept of a mineral belt along the southern margin of the San Juan Basin.

Mineralogy

The ore minerals are dominantly fine-grained, and they mainly occupy pore spaces in the host rock, but also partly replace it. These minerals consist of low-valent uranium and vanadium minerals and their oxidized products. Fine-grained carbonaceous material is abundantly and intimately associated with the ore minerals in some and perhaps all the deposits. Other accessory minerals consist of fine-grained sulfides in all deposits and fluorite in some. The uranium in many of the deposits is in part or largely in the hexavalent state, especially in those deposits that are above the present water table. It is assumed that this hexavalent uranium formed by oxidation of minerals containing tetravalent uranium. The occurrence of only the unoxidized ore minerals and the carbonaceous material will be described in detail.

Ore minerals

Coffinite is a uranium silicate with the approximate formula of $U(SiO_4)_{1-x}(OH)_{4x}$ (17). It is black, moderately hard, moderately heavy, and can be distinguished from uraninite only by its X-ray pattern. In the southern San Juan Basin area it is apparently the principal uranium mineral in unoxidized ores in sandstone. Typically it is extremely fine-grained and intimately associated with the carbonaceous material, mostly occupying pore spaces but partly replacing the sand grains. In the Woodrow deposit (see below), on the other hand, some coarse-grained coffinite that is apparently free from carbonaceous material has been found. It partly replaces massive pyrite and marcasite but is also veined by marcasite.

Uraninite (UO_2) is the common uranium mineral in the unoxidized deposits in the Todilto limestone. It is typically fine-grained. It mainly impregnates and replaces the limestone, in part as fine intergrowths with fluorite and a vanadium-bearing silicate (11, 12). It is also localized along siltstone laminae between bedding planes in the limestone. Uraninite has been recognized in a deposit in the Entrada sandstone, where it occurs as thin films on sand grains, in veinlets in a vanadium-bearing silicate, and as small concretions surrounded by pyrite.

As the vanadium content of the deposits in the southern San Juan Basin area is low, averaging about 0.15 percent V_2O_5, vanadium minerals are not conspicuous. Most of the low-valent vanadium in these deposits, however, occurs as a fine-grained micaceous mineral and is presumed to be one or more varieties of the vanadium-bearing silicates--mica, chlorite, or clay--that are common in the vanadium-bearing uranium deposits in other parts of the Colorado Plateau region. This material mainly occupies the pore spaces of the rock or replaces argillaceous material and detrital quartz and feldspar. Haggite and paramontroseite, both vanadium oxides, have also been reported as mineral occurrences.

Tyuyamunite $[Ca(UO_2)_2(VO_4)_2 \cdot 7\text{-}10.5H_2O]$ and carnotite $[K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O]$ are two common secondary uranium minerals where vanadium is available. Other common secondary uranium minerals are also present in places. These minerals mostly occur in open spaces, either pores or fractures.

Carbonaceous material

The sandstones containing most of the deposits in the southern San Juan Basin area are light-colored but the ore is various shades of gray. Three suites of samples from the Jackpile and Windwhip deposits, totaling 21 samples, reveal a close correlation between blackness/ and organic carbon content. The darker the rocks the higher the organic carbon content. Very light-gray/ rock, typical of barren host sandstone, contains 0.04 to 0.08 percent organic carbon; and the darkest sample--medium dark-gray to dark-gray/--reveals 2.16 percent organic carbon (Wayne Mountjoy, analyst). A suite of 52 samples from the Jackpile mine gave the following average assays: light-gray samples 0.04 percent U_3O_8; medium-gray samples, 0.31 percent U_3O_8; and dark-gray samples, 0.41 percent U_3O_8. As the organic carbon occupies much more volume than the equivalent weight percent of uranium and is at least as abundant by weight as uranium in these samples, the gray color of the samples and the ore is probably imparted by the carbonaceous material.

X-ray studies of the ore in sandstone show that much of the uranium is in the form of finely divided coffinite that is dispersed through the carbonaceous material. This carbonaceous material is apparently ubiquitous within the deposits, so its distribution reflects the gross form of the deposits. Most of it occurs as coatings on sand grains and intergranular fillings. Locally it is massive and partly replaces the

/ Rock-color chart, 1951, Geological Society of America detrital grains. Where coarse enough to separate mechanically from the rock it is a black brittle substance with a submetallic luster and a specific gravity of about 2.

Accessory minerals

Pyrite and marcasite are the common accessory minerals in all deposits, but they are generally sparse. These minerals mostly form minute crystals, irregular patches, or small nodules in the sandstone, partly replacing the sand grains. In the Woodrow deposit, on the other hand, pyrite and marcasite are much more abundant and form small incomplete replacement masses and locally boxwork structures controlled by the intersections of bedding and fracture planes in breccia fragments.

Trace amounts of fine-grained chalcopyrite, galena, and sphalerite are also present in many deposits.

Fine-grained fluorite, partly intergrown with uraninite, occurs as disseminated specks and in small irregularly shaped masses in places in deposits in the Todilto limestone.

Deposits in clastic sediments

The uranium deposits in clastic sediments have yielded most of the ore produced and contain most of the known ore reserves in the southern San Juan Basin mineral belt. Most of the deposits are in sandstone lenses in the Morrison formation; a few are in the Entrada sandstone and a few are in sandstone and carbonaceous shale of the Dakota sandstone. The deposits in the Dakota have been described by Gabelman (5, p. 422-429; 6, p. 303-319) and will not be discussed here.

The ore-bearing sandstones are fine- to coarse-grained, they are composed dominantly of quartz but contain various amounts of feldspars and other minerals common in sandstone as well as clay particles and thin mudstone layers. The ore and associated minerals including the fine-grained carbonaceous material, impregnate the sandstone, mostly occupying pore spaces but also partly replacing the sand grains. The ore bodies mostly occur as tabular layers that lie essentially parallel to the major bedding but which in detail transect bedding. These bodies are irregular in plan but tend to be elongate parallel to the trends of sandstone lenses, other sedimentary structures, and the two sets of pre-Dakota folds. They may be as much as several thousand feet in length and 50 feet or more thick. Small masses only a few feet across may be tabular or irregular in shape and roughly equidimensional.

Carbonized or silicified plant fossils are present in the Morrison formation in the southern San Juan Basin, but unlike many uranium deposits in other parts of the Colorado Plateau region, these fossils are not particularly abundant in the ore-bearing sandstone, and they are not conspicuously more abundant in the mineralized rock than in the surrounding barren sandstone. The plant fossils in the ore are commonly richly mineralized; but such materials a few feet above the ore are commonly barren of uranium. The possibility that this plant material influenced the localization of the deposits seems less likely in northwestern New Mexico than in other parts of the Plateau region.

On the other hand, many ore deposits and possibly all of the larger ore deposits contain much uranium-bearing organic carbon in the form of a black fine-grained material that is disseminated through the sandstone and coats and partly replaces the sand grains. The distribution of this material is apparently reflected by the gross form of the uranium deposits. Because the deposits assume a variety of forms that cut across sandstone bedding and crossbedding, as shown in figures 10, 12, and 13, it is assumed that the organic carbon was introduced into the sandstone in a fluid form. As the deposits composed of this material are commonly suspended at some level above the base and below the top of the sandstone, as shown in figures 9 and 13, it was probably introduced under some kind of water-table or fluid interface condition. The rather close association of this carbonaceous material and the uranium it contains suggests they were introduced at the same time.

Deposits in limestone

The Todilto limestone is fine- to medium-grained, but where it has been deformed it is partly recrystallized and coarse-grained. The ore minerals and the associated sulfides and fluorite are dominantly fine-grained, and they occur as replacements disseminated in the rock and along minor fractures and bedding planes. The ore bodies are localized where the limestone has been deformed by intraformational folding and faulting. Some ore bodies are irregular in shape but most are elongate and range from 20 to 30 feet in width and from 100 to a few thousand feet in length. Although most of the ore is in the lower part of the Todilto limestone, it may occur throughout the formation, and thus the ore bodies range in thickness from a few feet to as much as 20 feet or more. In a few places the ore bodies extend into the top few feet of the underlying Entrada sandstone or a few feet into the overlying Summerville formation.

The Todilto limestone is dark-colored, has a fetid odor, and contains as much as 1 percent or slightly more organic carbon. Some carbonaceous material is obviously concentrated as a dense black substance along parting planes in the thinly bedded parts of the formation, but some of it probably is disseminated throughout the rock. It is not obviously more abundant in or near ore than in the barren rock away from deposits. Analyses of the mill-pulp samples from 23 deposits showed a range from 0.05 to 0.14 percent organic carbon in the ores (Wayne Mountjoy, analyst). No data are available on the adjacent barren host rocks. More information is needed regarding the nature and distribution of this carbonaceous material and its possible influence on the localization of uranium minerals.

The deposit in a sandstone pipe

As only one deposit in a sandstone pipe, that at the Woodrow mine, has been observed in northwestern New Mexico, the description of it will be deferred to the section of this report where individual mines are described (see below).

Relations of the deposits to structural features

Sedimentary structures in sandstone, intraformational folds and faults in the Todilto limestone, pipelike collapse structures in sandstone and mudstone, and tectonic folds formed by regional deformation all influenced the localization of the uranium deposits. As far as the writers can determine, the only tectonic structures, however, that have directly or indirectly controlled the deposits are those that are related to the Jurassic, or first system of deformation.

Many ore deposits in the Morrison formation are in or near the central thick parts of sandstone lenses, and they tend to be elongate parallel to the trend of these lenses, suggesting that these parts of the lenses offered channelways for the ore-bearing solutions and favorable loci for ore deposition. Although such features as bedding planes, mudstone layers, cross-laminae, and grain-size variations within small sedimentation units show concentrating effects within deposits, sedimentary structures alone have localized only a few deposits. Commonly deposits transect sedimentation units within the host rocks, and the group of deposits that forms the Sandy mine area crosses the Todilto limestone-Entrada sandstone contact (see fig. 15). Likewise, many of the minor forms assumed by the ore within deposits sharply transect the sedimentary structures.

As all deposits in the Todilto limestone are associated with intraformational folds and faults, these structures apparently controlled the deposits. Likewise, the Woodrow--the only deposit in a sandstone pipe--was obviously localized by the structure it occupies. Although the top and bottom of the Woodrow pipe, the only pipe definitely known to be ore-bearing, are not visible, there is no definite evidence that this pipe or any of the others are connected with any other vertical structure that might have formed a through-going channelway for ascending or descending solutions. Thus, even though the Woodrow pipe certainly localized its deposit, its function may have been that of a locus of ore deposition rather than a channelway for solutions.

The folds resulting from regional deformation of Jurassic age probably caused and localized intraformational flowage of beds in the Todilto limestone and perhaps triggered the slumping in the sandstone pipes, and they may also have had some controlling influence on the position and direction of flow of the streams that deposited the ore-bearing sandstone lenses in the Morrison formation. If true, these folds had an indirect influence on the localization of the uranium deposits. With regard to later deformation, on the other hand, the writers have found no positive evidence that the positions or trends of deposits are in any way related to folding or fracturing. Furthermore, all through-going faults observed appear to have displaced the deposits. Although in places enrichment has occurred along regional faults and fractures within deposits, secondary concentration, of relatively recent age, seems to have been the more likely cause.

Localization and origin

The writers can offer only general suggestions regarding the localization and origin of the uranium deposits in the southern San Juan Basin mineral belt area. Although the three types of deposits certainly were localized by different controls, the writers favor the idea of a common origin. The deposits in the Morrison formation are in the central parts of sandstone lenses, form tabular layers that commonly transect bedding at low angles, and consist of an intimate mixture of ore minerals and carbonaceous material. An organic solution moving along the beds under water-table or fluid interface conditions conceivably could form deposits of this character if some local influence caused precipitation of constituents in solution. The same or a similar solution moving along the Todilto limestone and adjacent beds might have found conditions favorable for uranium precipitation in the limestone where it was deformed and partly recrystallized. In a somewhat similar manner the Woodrow pipe could have served as a barrier to precipitate uranium from passing solutions. No definite evidence as to the source of the ore-bearing solution or the metals contained is recognized. The deposits certainly formed after Jurassic deformation, probably after the Dakota sandstone was deposited, and before pronounced deformation in Tertiary time.

The Jackpile and satellitic deposits

The Jackpile uranium deposit, in the Laguna district, is probably the largest single deposit in the United States, and is one of the world's great producers of uranium. It constitutes about one-third of the total known uranium ore reserves in New Mexico, but its average grade is probably somewhat less than the average for all New Mexico uranium ores. The deposit is mined by a large-scale open-pit operation. The initial discovery was made in 1951 by airborne radiometric survey, and subsequent drilling proved a moderate-sized deposit, now known as the South ore body. In 1953, a larger ore body, now called the North ore body, was found a short distance to the north; this body supplies almost all the current production from the mine.

The Jackpile and associated deposits are in the "Jackpile" sandstone. The North ore body, which is the largest, consists of at least two large tabular ore layers (fig. 9). It is about 1,300 feet wide, several thousand feet long, and both layers total as much as 50 feet thick--probably averaging about 20 feet thick. It is elongated about N. 10° W. In additon a number of much smaller tabular deposits, as the Windwhip and the South ore body of the Jackpile mine, are satellitic to the North ore body.

The two ore layers of the North ore body are figuratively suspended about midway between the top and bottom of the "Jackpile" sandstone. These layers lie essentially parallel to the major bedding of the sandstone, (as shown in the longitudinal section, figure 9), though apparently they transect the bedding to some extent, as suggested in the cross section, figure 9, and certainly the top of the upper layer locally transects the crossbedding units, as shown in figure 10. The crosscutting relations shown in figure 9 are typical, though the upper boundary of ore is not typically a flat surface, and locally the edge of ore will follow bedding planes or thin discontinuous mudstone beds.

In contrast the grade variations within the deposit are strongly controlled by a multitude of sedimentary features. Clay galls, mudstone beds, and bedding planes commonly show concentrating effects, and large pods of high-grade ore commonly conform with trough cross-stratification. In addition, very sparse intraformational faults and joints show some concentrating effect.

In the mine area the Cretaceous rocks dip gently about N. 20° W., with local flattening and steepening, and the North ore body appears to conform with the structural dip.

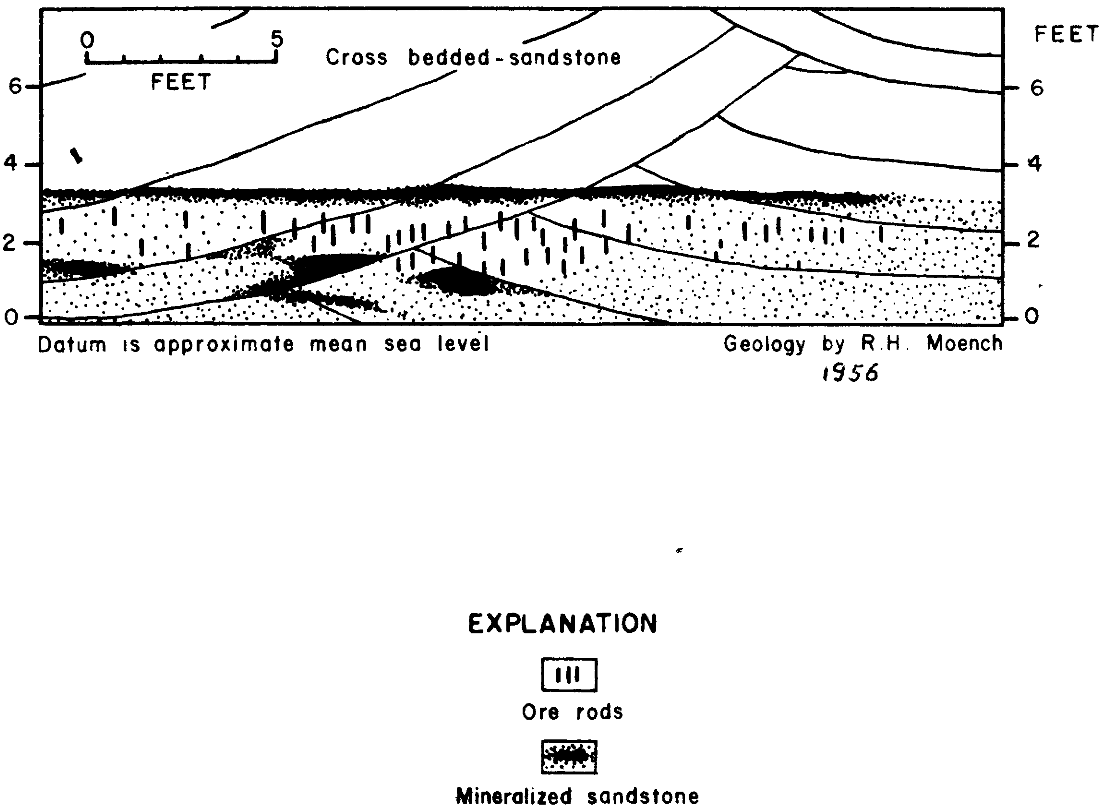

FIGURE 10-- FIELD SKETCH SHOWING RELATION OF TOP OF JACKPILE URANIUM DEPOSIT TO CROSSBEDDING IN SANDSTONE

The long dimension of the North ore body may parallel the axis of a pre-Dakota anticline. In figure 9, cross section, this anticline is defined by two mudstone beds within the "Jackpile" sandstone. The uppermost mudstone bed, in the vicinity of the sandstone pipe, rises a short distance towards the center of the section, and is truncated by the base of the Dakota sandstone. The lower mudstone bed rises to a crest just west of the center of the deposit, and then falls a short distance and pinches out on the west flank of the anticline. For lack of sufficient exposure the breadth, amplitude, and trend of the anticline are not known. Other folds nearby, however, are well exposed and trend N. 10° W. As this is a persistent regional trend of one set of pre-Dakota folds, it is likely that the fold exposed in the Jackpile mine also trends N. 10° W. and coextends with the long dimension of the North ore body.

An extremely irregular complex diabase sill cuts much of the Jackpile deposit. This sill is related to the late Tertiary diabase dikes and sills that are abundant throughout the Laguna district. It averages several feet thick and is essentially horizontal, but cuts randomly through the deposit--locally rising well above or falling well below it. In figure 11 the sill is shown to cut through the top of the deposit. Here, the deposit is displaced by an amount equivalent to the thickness of the sill, indicating that the sill was emplaced later than the uranium deposit.

A sandstone pipe is exposed on the east side of the North ore body (fig. 9). The top of this pipe is shown in figure 8 and is described above in connection with sandstone pipes. Only the upper part of the pipe is exposed, the top of which is about 40 feet above the top of the ore body. Although organic materials are abundant within the pipe, they

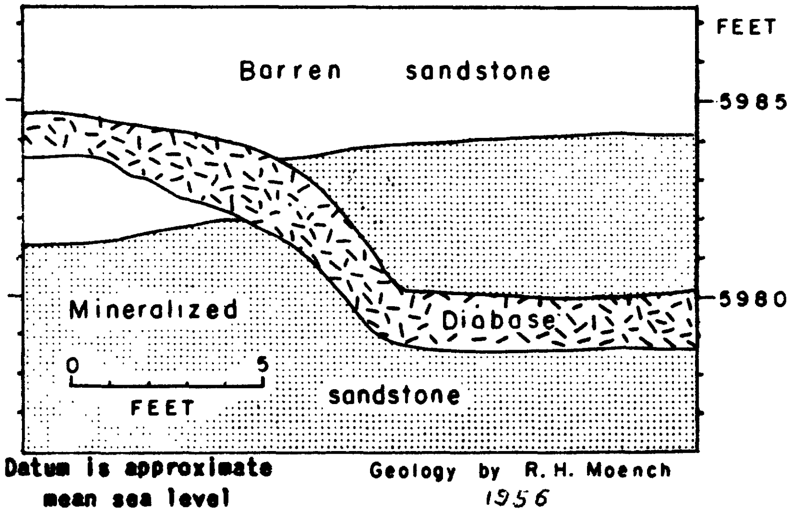

Figure 11.--Field sketch showing displacement of Jackpile uranium deposit by diabase sill.

are absent in the wall rocks, and the pipe is essentially barren of uranium where exposed. Where it intersects the approximate level of the North ore body, however, it reportedly contains ore.

Vertical ore rods of uraniferous carbonaceous material constitute a unique and interesting feature of the deposit. Some of the rods are shown in figure 12. They are vertical cylinders as much as 2 inches in diameter and 4 feet high, which tend to occupy the lower grade parts of the deposit (fig. 10) and are especially abundant in the low-grade zone between the two main ore layers (fig. 9). The bedding is undisturbed, although the rods cut across it, and many rods terminate at their tops or bottoms at bedding planes, while others feather out along the bedding. Very commonly the rods are zoned, consisting of a core of uraniferous carbonaceous material, bounded by a thin pyritic zone.

A number of relatively small uranium deposits have a distribution that is satellitic to the Jackpile deposit. These smaller deposits are similar to the Jackpile with respect to form, composition, and relation to the host sandstone. Two of the satellitic deposits are described briefly below.

The South ore body of the Jackpile mine is near the southwest corner of the North ore body. It has the same vertical position in the "Jackpile" sandstone, and likewise it consists of two main tabular ore layers. In plan it is oval, about 350 feet wide, 750 feet long, and as much as 50 feet thick. It is elongate about N. 70° E.--nearly at right angles to the elongation of the North ore body.

Figure 12.--Photograph of vertical ore rods, Jackpile mine.

The Windwhip deposit is on the west side of the Jackpile deposit. Its horizontal dimensions are not known to the writers, but it is considerably smaller than the South ore body. The Windwhip deposit is suspended within the "Jackpile" sandstone, but is stratigraphically higher than the Jackpile deposit. It is about 15 feet below the top of the "Jackpile" sandstone, and probably overlaps the western edge of the Jackpile deposit.

The general character and distribution of ore in the Windwhip deposit is illustrated in figure 13. Here the ore conforms locally to the sedimentary structures, or transects such structures at a low angle. In many places, however, the ore has a smoothly curved edge that cuts sharply across the bedding. Such features are similar to the roll structures described by Fischer (4) and Shawe (15, 16) in other parts of the Colorado Plateau.

The Poison Canyon and associated deposits

The Poison Canyon deposit is in the Ambrosia Lake district. It is one of the few large deposits in the district that is sufficiently developed to allow effective study. The general mineralogy and configuration of this deposit have been described by Dodd (2, 3). Dodd's description, combined with the results of more recent work are summarized below. The deposit illustrates a more direct relation to sedimentary features than has been observed in deposits of the Laguna district.

The Poison Canyon deposit is in the "Poison Canyon" sandstone of the Morrison formation. It is a tabular deposit consisting of many subparallel layers. Individual layers are as much as 200 feet wide and 20 feet thick, and they form an aggregate as much as 700 feet wide

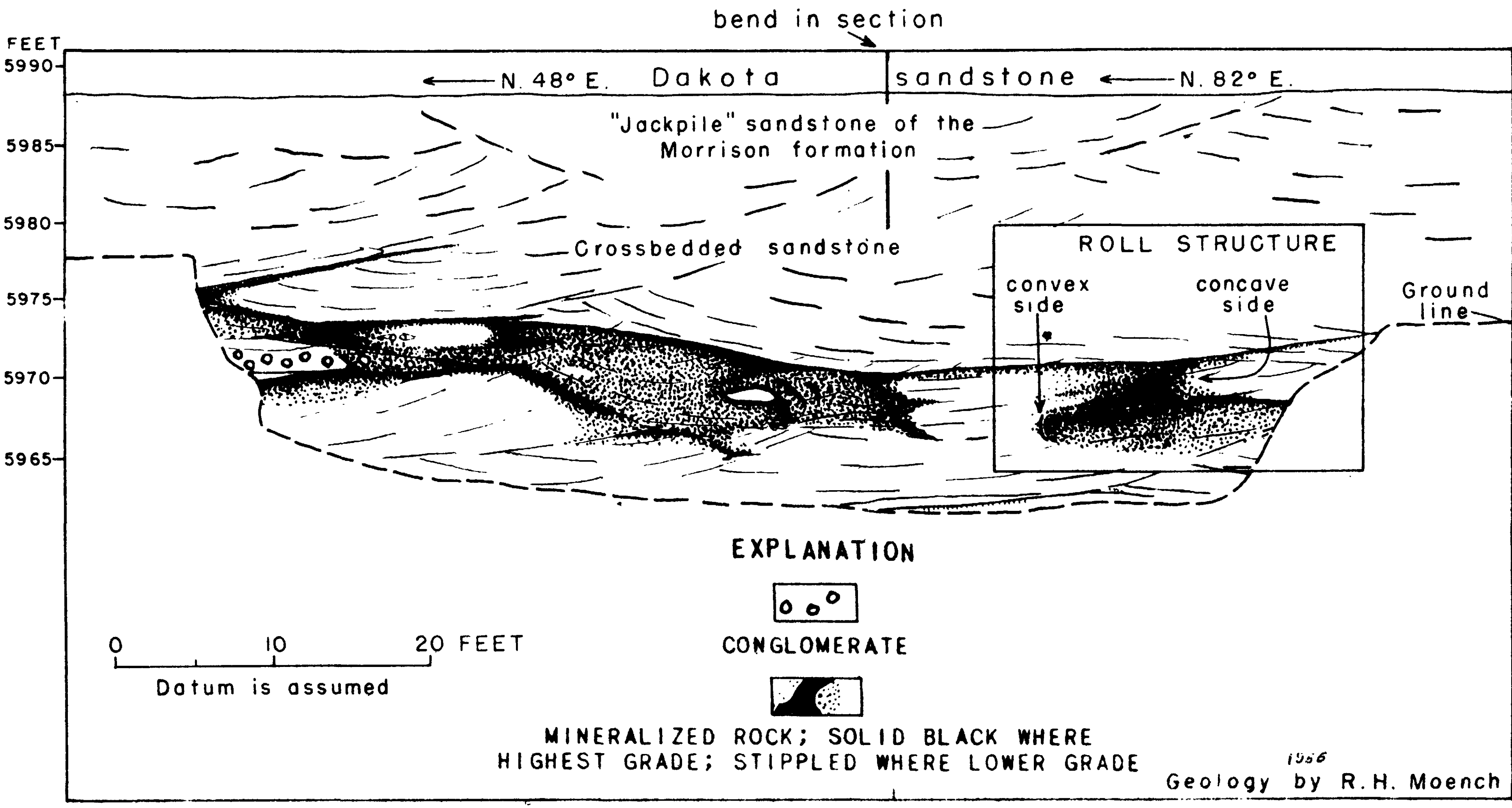

FIGURE ~~12~~ 13.—GEOLOGIC WALL MAP OF THE WINDWHIP DEPOSIT.

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and 35 feet thick. The layers and the aggregate are all strongly elongated in an easterly direction. The deposit is near the base of the host sandstone, and concentrations are most abundant above or below thin mudstone beds. Dodd (2, 3) states that the deposit is elongate along the trend of sedimentary structures, and is localized in the central thick coarse-grained part of the unit. He illustrates (2, fig. 8) that the Poison Canyon deposit and also the Mesa Top deposit, immediately to the east of it, are in, and coextensive with, a "composite" channel in the "Poison Canyon" sandstone. Recent work bears out these relations, and subsurface information reveals that the "composite" channel extends eastward in a broad arc at least 7 miles long (fig. 4). It is referred to here as the Poison Canyon trend.

The deposit is cut by a number of northward-trending faults, and all available evidence suggests that the faults are younger than the deposit. The ore layers are displaced by the same amount of throw as the units in the host rock. Dodd (2, 3) states that the grade and thickness of the ore increases adjacent to the faults, but also states that only secondary minerals are found on fault and fracture surfaces. More recent work has revealed that the higher grade concentrations adjacent to the faults are made up of minerals containing hexavalent uranium. The deposit is most oxidized near the faults, and it is probable that these concentrations formed by near-surface redistribution of uranium by ground water.

The uranium deposits north of the Poison Canyon deposit

North of the Poison Canyon deposit the uranium deposits of the Ambrosia Lake district constitute several multi-million-ton and numerous smaller deposits that account for more than one-half of the total uranium reserves in the southern part of the San Juan Basin. Unfortunately they have not been developed sufficiently to study in detail. With respect to form, composition, and structural and stratigraphic relations, however, they are known to be similar to the other deposits in the Morrison formation. For lack of detailed information, the deposits of this area are described collectively.

As shown by their approximate outlines in figure 4, the deposits in this area, the Ambrosia trend, constitute an elongate easterly-trending group that is essentially parallel to the Poison Canyon trend. The approximate vertical distribution of the deposits within the Morrison formation is shown in figure 5. Individual deposits are essentially tabular and are figuratively suspended within the host sandstones (fig. 5) similar to the deposits in the Morrison and Entrada formations of the Laguna district. In general the deposits occur where the sandstones are coarsest and, locally, occur in one or more zones having an aggregate thickness of as much as 100 feet. In general, however, the deposits have average thicknesses that range from several feet to several tens of feet. Like the Jackpile deposit, they generally follow the bedding, but locally transect sedimentary units (see just right of the center of section C-C', fig. 5).

Most of the deposits, including all those that contain more than about 1 million tons of material, are in the Westwater Canyon member; the others are in the Brushy Basin member. As pointed out above in the section on stratigraphy, most of the deposits are near the central part of a thick mass of sandstone (see fig. 5), which is more extensive and uniform in an easterly direction than a northerly direction, except where it thins markedly over the Ambrosia dome.

The authors interpret that the belt of deposits in this part of the Ambrosia Lake district is coextensive with and controlled by the easterly trend of the thicker part of the sandstone mass. Absence of uranium deposits over the crest of the Ambrosia dome and the tendency to clustering of deposits around its periphery are probably related to the thinning of the host sandstone mass over the dome rather than to closure on the dome.

The Woodrow deposit

The Woodrow deposit, about 1 mile east of the Jackpile mine, is unique in the district, and probably on the Colorado Plateau. It is small, but exceedingly high grade, the ore averaging nearly 2 percent uranium. It is particularly interesting, however, because it occupies a structure that may best be termed a sandstone pipe. The pipe (fig. 14) is nearly vertical, has a known height of about 230 feet, and a maximum diameter of about 35 feet. It is bounded by a complex branching ring fault. The wall rocks include the "Jackpile" sandstone, and underlying beds of mudstone and sandstone. With the exception of probable down-warping and faulting in the near vicinity of the pipe, these rocks are essentially undeformed. The core of the pipe is made up of a hetero-geneous mixture of sandstone and mudstone which appears to have been derived from the nearby wall rocks. Near the top of the pipe sandstone predom-inates; near the bottom mudstone predominates. The transition zone is

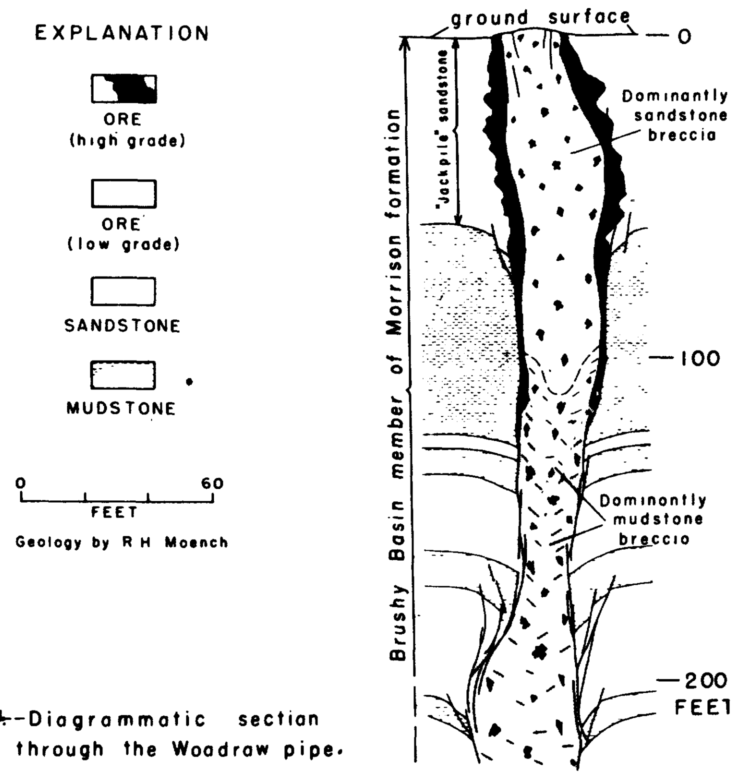

Figure 14--Diagrammatic section through the Woodraw pipe.

about 35 feet below the base of the "Jackpile" sandstone, and probably indicates the amount of downward displacement of the core with respect to the wall rocks. Carbonaceous materials are abundant within the pipe, and a few fossil bone fragments have been found.

In the upper part of the pipe the ore is exceptionally high grade, and is concentrated mainly along the boundary ring fault. Here the core of the pipe is essentially barren, but the ore locally extends several feet outward into the "Jackpile" sandstone. In the lower part of the pipe the ore is much lower grade, though still higher grade than the district average, and is more or less homogeneously distributed throughout the core.

The ore concentration along the ring fault is a replacement, not a fissure filling. Massive sulfides, as pyrite and marcasite, commonly show relict bedding, in which the outlines of individual grains are visible. High-grade coffinite-sulfide mixtures locally show boxwork textures, controlled by bedding-fracture intersections.

As the top of the Woodrow pipe has been eroded and its bottom has not been found, its original stratigraphic range, age, and origin cannot be determined. That part of the pipe which is well exposed, however, is strikingly similar to the many hundreds of sandstone pipes that are exposed throughout the Laguna district (see structural geology). Although the Woodrow pipe is mineralized, the writers interpret that it is the same type of structure as the others. If so, the ring fault acted as a locus of uranium deposition, rather than as a conduit.

The Sandy mine

The Sandy mine, which is in the Laguna district, is in an area about 2,000 feet wide by 4,000 feet long, referred to here as the Sandy mine area. It contains many small, locally high-grade deposits, including the Sandy, which occur in the Entrada sandstone and Todilto limestone. Little uranium ore has been produced from the area, but it is discussed to illustrate (1) the occurrence of uranium deposits in the Entrada sandstone and Todilto limestone, (2) the relation of deposits in the respective host rocks to one another and to a pre-Dakota monocline, and (3) the relation of the deposits to the diabasic sills and dikes.

The area is underlain by the Summerville formation, Todilto limestone, and Entrada sandstone. Late Tertiary diabase dikes, 1 to 5 feet thick, and a great many diabase sills, as much as 75 feet thick, cut and have metamorphosed[1] to some extent all of these rocks and many of the uranium deposits.

[1] The metamorphism of the rocks and ores will be treated in a forthcoming report.

The dominant structure in the area is a monocline that is related to the major easterly trending set of pre-Dakota folds. The monocline trends easterly to northeasterly across the area. Its steep flank dips southward, is about 1,300 feet broad, and its maximum structural relief in the mine area is about 110 feet.

The Todilto limestone in the area contains a multitide of intraformational folds. These are small but pronounced structures, with amplitudes about equal to their breadths. The largest folds have a breadth of about 20 feet, and involve the entire thickness of limestone. The smallest are less than half an inch broad and commonly have the relation of drag to the larger folds. In sections the folds have a variety of shapes, the most common of which is that of an asymmetric fan. The axes of the intraformational folds on the flanks and near the anticlinal bend of the monocline mostly parallel the larger structure, but near the synclinal bend they are highly sinuous and are not systematically oriented.

The known uranium deposits of the area constitute a group of deposits that are confined to the steep flank and anticlinal and synclinal beds of the monocline. Figure 15 illustrates the relation of the group of deposits to the monocline and to the two host rocks. To better illustrate these relations the diabasic dikes and sills have been removed from the section, and the structure restored to its pre-diabase position. This was done because the diabase is younger than the uranium deposits and distorts the earlier structure. Near the anticlinal bend of the monocline most of the deposits are within the Entrada sandstone. A few very small deposits are on the formational boundary, but none is in the Todilto limestone. Near the synclinal bend the deposits are all within the stratigraphically higher Todilto limestone. Also, downdip some deposits pass from Entrada sandstone into Todilto limestone. The relief on the group of deposits, therefore, is less than the relief on the monocline, and the group transects the formational boundary.

Figure 16 illustrates the essential physical features of a typical deposit in the Entrada sandstone. The deposit is tabular--about twice as long as it is wide. It is suspended within its host sandstone--not bounded by any visible sedimentary or structural feature. In addition

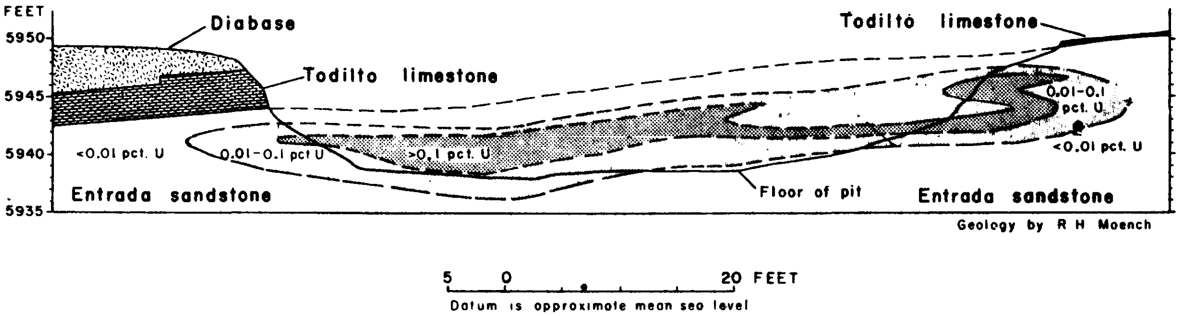

Figure16.--Section through uranium deposit in Entrada sandstone, Sandy mine.

it shows roll structures, as do many of the small deposits in sandstone. The axes of these structures parallel the average strike of crossbedding.

The deposits in the Todilto limestone are almost wholly associated with intraformational limestone folds. The deposits, therefore, are stringlike and highly sinuous in plan. Figure 17 illustrates in section the distribution of uranium with respect to the central part of a limestone fold. The uranium deposit, as indicated, by the one-tenth and higher milliroentgen isorad, is dominantly in the massive thick-bedded limestone, which is in the center and at the base of the fold. In section the form of the deposit is crudely that of a reversed L, and it is coextensive with the fold.

The deposit is separated into three parts by two diabasic sills, which are younger than the deposit. As the lower sill is about 20 feet thick, the lowermost part of the deposit is not shown in figure 16. The upper sill cuts the top of the deposit, and truncates all isorads higher than 0.05 milliroentgens. The 0.05 milliroentgen isorad reflects only an increase in general radioactivity toward the deposit. The highest grade parts of the deposit, and the major limestone units above the sill are all displaced to the right with respect to the same features below the sill. The lower sill cuts the base of the deposit. As this part of the deposit is the basal part of the reversed L, the higher grade isorads spread out at the base of the sill as well as at the top.

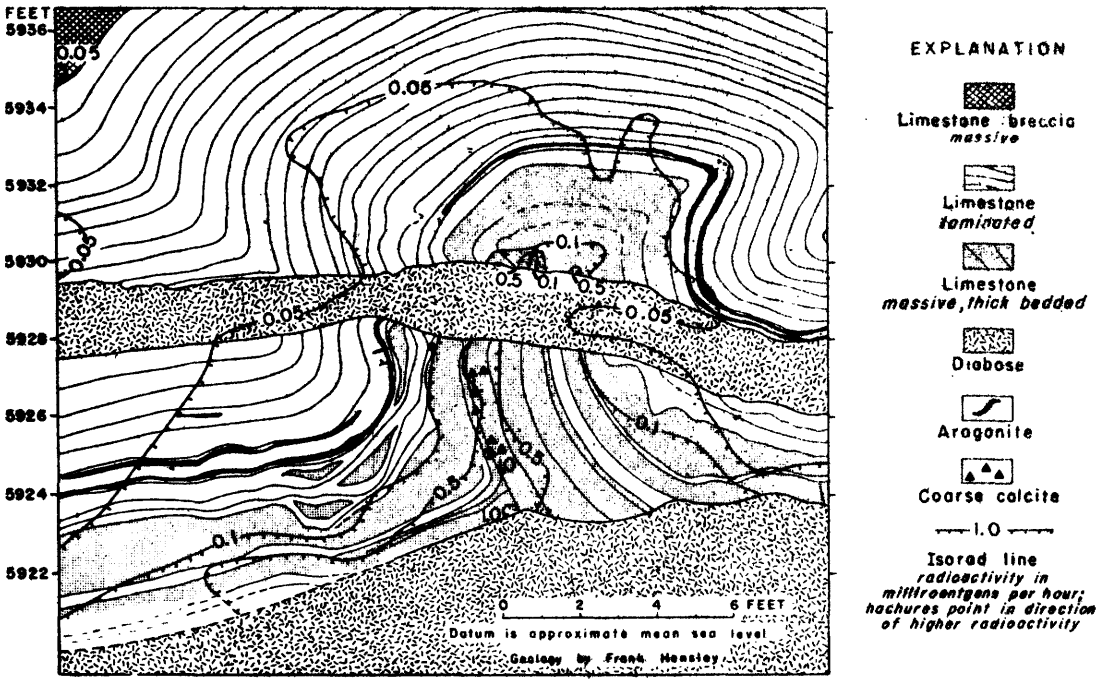

Figure 17.--Section across uranium deposit in Todilto limestone, Sandy mine area.

The F-33 mine

The F-33 deposit, in the Ambrosia Lake district (fig. 2), is an excellent example of an average-sized uranium deposit in the Todilto limestone. It is discussed here to illustrate the distribution of the deposit with respect to the lithologic units in the limestone, and to minor folds.

The Todilto limestone in this mine contains the lower "platy," medial "crinkly," and upper "massive" units that persist throughout most of the region (see Stratigraphy). These rocks are strongly deformed, and they define a number of folds and faulted folds (fig. 18). In contrast with much of the folding in the Todilto limestone the largest fold exposed in this mine involves the upper part of the Entrada sandstone. The best-developed fold in the F-33 mine is an anticline that has a breadth in excess of 50 feet and a maximum height of about 7 feet. The northern flank of the anticline is steeper than the southern flank and is locally overturned and thrusted (fig. 18). This structure, as well as the smaller linear structures in the mine, is oriented, with some variation, about N. 70° E.

The uranium deposit is contained within all three units of the Todilto limestone (fig. 18). Although most of the ore is in the "crinkly" and "massive" zones, there appears to be little direct relation between lithologic changes and distribution of the uranium deposit.

The deposit and the fold are closely coextensive. The deposit as a whole is about 100 feet wide, as much as 15 feet thick, and more than 1,200 feet long. Its long dimension, oriented about N. 70° E., is closely coextensive with the fold. Although the width of the deposit is much greater than the breadth of the anticline, its highest grade parts are mostly in the structural low just north of the steep or overturned flank (fig. 18).

RESOURCES IN UNEXPLORED GROUND

The ore-bearing rocks between Gallup and Laguna dip northward, so, generally speaking, there is only one line of outcrop of these formations (fig. 2). The known deposits have been found at this outcrop or, by subsurface exploration, at moderately shallow depths within a few miles north of this outcrop. It is possible that the pattern or frequency of distribution of these deposits at and near the outcrop continues in these formations northward under increasing depth of burial toward the center of the San Juan Basin; under these circumstances the undiscovered resources would be extremely large. On the basis of interpretations from known geologic relations, however, it seems more likely that the deposits will tend to be clustered in a zone at least 20 miles wide behind the present outcrop; this idea permits the concept of the southern San Juan Basin mineral belt. Even though this concept restricts the favorable ground geographically, the amount of unexplored ground within the limits of this belt is enough to contain several times as much uranium resources as is now known. The gologic evidence and reasoning for this belt are reviewed below.

A short distance south of the Gallup-Laguna area the Morrison formation is cut out by the unconformity that underlies the Dakota sandstone. Although deposition of the Morrison undoubtedly extended a short distance to the south of this line, the existence of a broad area of nondeposition in central and southern New Mexico (13) suggests that the southern limit of deposition of the Morrison was not far south of its present southern limit (fig. 1).

The Todilto limestone also pinches out in a depositional edge along a line a short distance south of Laguna and east of Gallup, and still farther south the Entrada is cut out by pre-Dakota erosion. The Gallup-Laguna area seems to have been close to the southern edge of the general basin of deposition in which the Jurassic rocks of the Colorado Plateau region accumulated. Perhaps the tectonic movements that during the Jurassic formed and sustained this basin caused the minor flexures in the Gallup-Laguna area. These flexures probably gave rise to the intraformational folds in the Todilto limestone, preparing the rock for later ore deposition; and these flexures may also have had some control on the positions and trends of the streams that formed the sandstone lenses which are hosts for the deposits in the Morrison formation. At any rate, because of these marginal relations, rocks favorable for ore deposits did not extend much farther south than the present line of outcrop between Gallup and Laguna.

Evidence to limit and predict the northern edge of this conceived belt is even more tenuous, for the ore-bearing rocks are buried. Of course, the pre-Dakota flexuring could have extended northward into the basin of Jurassic deposition, but it is more likely that this deformation was concentrated along, and perhaps restricted to, the basin margin. In the Laguna district the "Jackpile" sandstone thins northward from the Jackpile mine; and no significant uranium deposits are known more than a few miles north of the Jackpile mine. There has been little exploration north of the known deposits in the Ambrosia Lake and Gallup districts because of the increasing depth of burial of the ore-bearing rocks. There is some evidence, however, that the ore-bearing sandstones locally thin northward from the vicinity of the deposits in the Ambrosia Lake district. Where the sandstones show no apparent thinning they become more uniform in character. This greater uniformity of the sandstones suggests a depositional change basinward, possibly to quieter, or more uniform fluvial conditions, and the deposition of sediments that were probably unfavorable for the formation of significant uranium deposits.

In summary, the reasons for the existence of this belt of known uranium deposits are not fully known; the fact remains, however, that the belt parallels a number of controlling and definitive geologic features. In addition to the Jurassic highland and the southern limits of the Todilto limestone and the Morrison formation, it parallels the easterly trend of the major Jurassic folds, the dominant orientation of the intraformational folds in the Todilto limestone, the elongation of the thickest parts of the host sandstones of the Morrison formation, the dominant known sedimentary trends within these host sandstones, and, finally, it parallels the individual belts of deposits, as the Poison Canyon and Ambrosia trends. The southern San Juan Basin mineral belt can therefore be defined as a geologic feature that is controlled by a combination of several geologic structures and events.

SUMMARY AND CONCLUSIONS

Uranium deposits along the southern margin of the San Juan Basin occur in the Morrison, Todilto, and Entrada formations of Jurassic age and the Dakota sandstone of Cretaceous age. The known reserves have a total value of more than one billion dollars; most of these reserves are in the Morrison formation.

In the Morrison formation the ore minerals of the principal deposits are intimately mixed with a carbonaceous material that impregnates sandstone and forms tabular bodies that lie nearly parallel to the bedding. Most deposits are in the central parts of thick sandstone lenses. Gentle folding during Jurassic time may have controlled the positions of the streams that formed these sandstone lenses.

The ore minerals in the Todilto limestone impregnate and replace the limestone where it has been deformed by intraformational folding and faulting. This deformation may have been caused by the flowage of unconsolidated lime muds on the flanks of the Jurassic flexures, for the intraformational folds are localized along these flexures and many are elongate parallel to them. Typically the ore bodies in the Todilto are long but narrow.

Sandstone pipes are numerous in the eastern part of the area and also are localized along the flanks of these Jurassic flexures. Their positions and their habits suggest that they resulted from some slumping action before consolidation of the beds they cut. Only one of the several hundred pipes known has yielded uranium ore, and only one other reportedly contains ore. It is likely that these pipes provided loci for deposition of uranium, rather than channelways for ascending or descending uranium-bearing solutions.

Deformation during Jurassic time may have had some direct or indirect influence on the localization of the uranium deposits in the rocks of Jurassic age; there is no definite evidence that later tectonic structures had a genetic influence on the deposits. Although the genesis of the deposits is not known, it is believed that all of them had a common origin. It is suggested that solutions circulating through the rocks under water-table conditions could have formed deposits that would have habits like those in this area.

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