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URANIUM DEPOSITS OF THE GRANTS REGION

By

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Editor's Note:

This contribution to the Guidebook was written in 1966 for publication in the forthcoming Graton-Sales Volume, which will be published early in 1968 by the American Institute of Mining, Metallurgical and Petroleum Engineers as a sequel to the well known classic "Ore Deposits of the Western States," published by AIME in 1933. Co-author Kittel has condensed and updated the article for publication at this time.

INTRODUCTION

The Grants uranium region comprises several contiguous mining districts that contain a belt of uranium occurrences more than 85 miles in length. For the most part the uranium mineralization occurs in the Jurassic sandstones and limestones that comprise part of the southern edge of the San Juan Basin of northwestern New Mexico.

The districts have been designated Grants, Gallup, and Laguna (Kelley, 1963), and comprise the Gallup, Churchrock, Smith Lake Ambrosia Lake, Grants, North Laguna, and South Laguna mining areas. The districts are separated physiographically by Mount Taylor, a late Tertiary volcano that rises from basalt-capped Mesa Chivato to an elevation of 11,389 feet above sea level. (fig 1). The Laguna district lies east of Mesa Chivato and the Grants and Gallup districts lie generally west of it.

Mining areas within the Grants and Gallup districts lie along a series of southward-facing cliffs, cuestas, mesas, and soft-rock valleys. The Ambrosia Lake area is the major producer of the two districts; it is in a valley that was formed by erosion down to lower Cretaceous sandstones and shale. The valley is about 12 miles long, three miles wide, and is at about 7,000 feet elevation. Ore from the two districts is processed at mills, operated by Kerr-McGee Corporation and Homestake-Sapin Partners.

At present all production from the Laguna district comes from Anaconda's large Paguate open pit mine. It is shipped by rail to Anaconda's mill near Bluewater, where it is treated by an acid leach process.

* Now with Humble Oil & Refining Co., Denver, Colorado.

DISCOVERY, EXPLORATION, AND MINING

The occurrence of uranium minerals in outcrops in the Grants districts was known as early as 1920. No mining of them was done until after 1950, however, following a well publicized find by Paddy Martinez of yellow carnotite-type ores in the Todilto Limestone near Haystack Mountain.

The first production was small tonnage mined from outcrops of the Todilto limestone and the Poison Canyon sandstone tongue of the upper Morrison and shipped to the AEC buying station at Monticello, Utah. Later intense exploration and development of these outcrop ore bodies brought about the establishment in 1952 of an AEC buying station in conjunction with Anaconda's mill that was being built near Bluewater. The mill, designed to treat limestone ores, was completed in 1953, and was followed two years later by the completion of a second mill to treat sandstone ores.

Many types of equipment were used to explore for new deposits and to outline and delineate the known ones. Among them were geiger counters, scintillation counters, either handcarried or mounted in ground or airborne vehicles, various types of drilling, and electric-gamma ray logging.

Nearly all of the first ore produced came from open pit mines. Maximum production up to 1954 amounted to about 300 tons per day from the Haystack operation owned by the AT&SF Railway. The first underground mines in the Grants districts produced about 20 to 200 tons per day, and gradually became larger operations as discoveries were made by drilling back from the uranium-bearing outcrops. Late in 1954 the Jackpile mine (later to become the world's largest open pit uranium mine) was brought into large-scale production.

The first discovery of uranium in the Ambrosia Lake area was made by Louis Lothman early in 1955. About a year and a half later more than 50 drills were exploring in that area, resulting in the outlining of the largest single deposit, or closely related group of deposits, known in the world. Later smaller discoveries were made in the Smith Lake and Churchrock areas between Ambrosia Lake and Gallup.

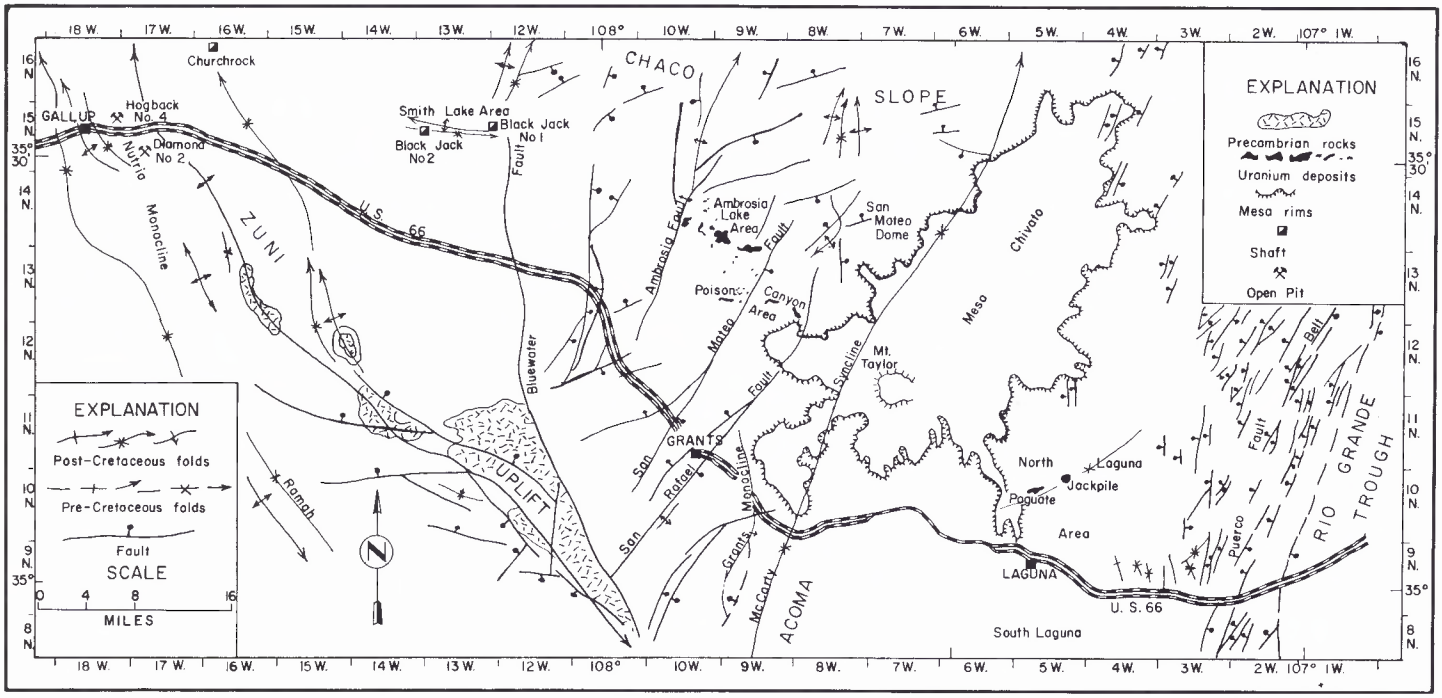


FIGURE 1.

Geologic features of the Grants uranium region.

Prior to the uranium discoveries in the Grants districts the United States was for the most part dependent upon foreign sources of uranium to meet its defense needs. During the years that followed, and up to the start of 1967, a little over one billion dollars worth of concentrates has been produced from mills operated by Anaconda, Homestake-New Mexico Partners, Homestake-Sapin Partners (now idle), and Kerr-McGee Industries.

STRATIGRAPHY

The sedimentary rocks of the Grants districts range in age from Pennsylvanian to Cretaceous. Precambrian gneiss, schist, and granite are exposed in the core of the Zuni Mountains, and overlying these rocks, on the flanks of the Zunis, are the Pennsylvanian Magdalena Formation (125 feet), Permian Abo, Yeso, and San Andres Formations (650, 900, 300 feet), and Triassic Dockum Group (1600 feet) (Smith, 1957). Uranium deposits of consequence are almost entirely in the Jurassic, but a few small deposits have been mined from the lowermost beds of the Cretaceous. The currently prevailing stratigraphic nomenclature of the significant units in the Grants districts is as follows:

SYSTEM	UNITS	THICKNESS
Cretaceous:	Hosta Sandstone	150+
	Crevasse Canyon Formation	800-1000
	Gallup Sandstone Member	180- 250
	Mancos Shale (including Tres Hermanos)	800-1000
	Dakota Sandstone (sandstone, shale)	10- 150
Jurassic:	Morrison Formation	100- 600
	Brushy Basin Shale Member including Jackpile sandstone	20- 350
	Westwater Canyon Sandstone Member including "Poison Canyon" tongue	0- 300
	Recapture Shale Member	50- 175
	Bluff Sandstone	130- 400
	Summerville Formation (mudstone, sandstone)	50- 220
	Todilto Formation (gypsum, limestone)	0- 125
	Entrada Sandstone	150- 250
Triassic:	Chinle Formation	1000-1600

The Todilto Limestone has accounted for about 4.2 percent of the uranium produced to date in the Grants districts. In the Laguna district it is up to 125 feet thick and consists of 5 to 35 feet of fetid gray laminated limestone overlain by as much as 90 feet of gypsum and anhydrite. The basal limestone consists of laminated to massive beds, and the upper part is massive. The gypsum zone pinches out southward and is only locally present south of U.S. Highway 66. In the Grants and Ambrosia Lake area the limestone only is present, and this commonly is a tripartite unit 15 to 30 feet thick consisting of parallel laminated limestone and some siltstone at the base, a middle unit of crinkled thin limestone beds, and an upper massive, often coarsely crystalline, limestone. The upper unit is locally absent.

The basal platy zone is up to 15 feet thick, thin-bedded, and light gray to grayish-brown. This carbonaceous partings commonly occur along bedding planes, and recrystallization has occurred along joint planes and in folds. The medial limestone zone is up to six feet thick, extremely crenulated, usually recrystallized, and of the

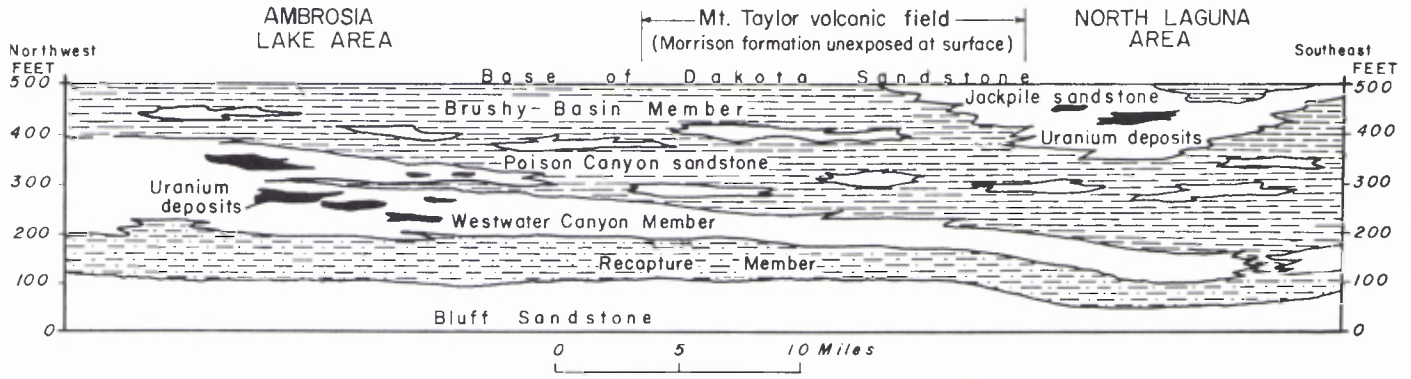


FIGURE 2.

Stratigraphic diagram of the Morrison Formation in the Grants region, showing the relationship of its members between the Ambrosia Lake and North Laguna areas.

same colors as the platy part. Because of these crenulated bedding planes, this middle unit is locally referred to as the "crinkly" zone. The upper massive limestone is usually assigned to the Todilto although some assign it to a transition zone between the Todilto and Summerville formations.

The Westwater Canyon sandstone is quite irregular in thickness owing to lensing and lateral gradations into Brushy Basin or Recapture type mudstone and claystone. The "Poison Canyon" sandstone, which is up to 85 feet thick, is a tongue of Westwater Canyon sandstone in the Brushy Basin Member. The Westwater averages about 150 feet thick in the Ambrosia Lake area, but locally it may reach 300 feet or thin and disappear into zones of arenaceous mudstone. Its sandstone beds vary from parallel-bedded to irregularly cross-bedded. The color may be light gray, yellow-brown, red-brown, or grayish black, depending on proximity to the surface, mineralization, or content of organic material. The sand is fine to coarse, poorly sorted, and locally conglomeratic. The composition is feldspathic with considerable sanidine (Austin, 1963). Locally the quartz fraction contains slightly corroded, high-temperature, biypramidal phenocrysts. In general the composition indicates an acidic tuffaceous derivation for many of the beds.

The Brushy Basin resembles the Recapture and consists of greenish gray and reddish brown mudstones with numerous Westwater-type sandstone lenses, channel fills, or arenaceous zones. It is as much as 500 feet thick, but may be much less, owing partly to intertonguing with the underlying Westwater Canyon and Bluff sandstone tongues, but principally to plication at the extensive pre-Dakota erosion surface.

In the Laguna district the Westwater and Recapture units are thought to have thinned markedly, and both are relegated by Hilpert (1963) to about the lower 100 feet of the Morrison (fig. 2). On the other hand, the overlying Brushy Basin is thought to have thickened to about 500 feet (Hilpert and Moench, 1960). In the vicinity of the Jackpile mine as much as 220 feet of the uppermost part of this thickness consists of a large sandstone channel deposit (Jackpile sandstone) preserved in a broad pre-Dakota structural downwarp that was more or less parallel to the northeasterly depositional trend.

Over 94 percent of the uranium production from the Grants districts has come from the Morrison sandstones.

IGNEOUS ROCKS

A variety of shallow intrusive rocks and rather extensive basaltic flows constitute the principal igneous rocks found in the region. Diabase dikes and sills are common in the Laguna district; most of these are less than 10 feet wide, but a few that branch from plugs are several tens of feet wide. Dike trends are principally northerly and northwesterly (the maximum known length is about 10 miles), and sills are found in many stratigraphic horizons in the district.

Numerous basaltic necks occur in or adjacent to the Mount Taylor valcanic field. Most of these fed volcanos, and several sections of partly dissected cones and feeder necks are exposed along the edge of Mesa Chivato and lesser volcanic-capped mesas. These necks may consist of solid lava, lava breccia, or lava-sedimentary mixed breccias.

About seven miles northeast of Grants, in what is referred to as East Grants Ridge, there is an elliptically shaped dome one to one and one-half miles in diameter. The central part is aphanitic, lithophysaical, flow-banded rhyolite surrounded by a peripheral-chilled sheath of obsidian and perlite.

STRUCTURE

The principal regional structures of the area are the Zuni uplift and the Acoma sag. The Zuni uplift is a broad northwest-trending upwarp asymmetrical to the southwest, and the Acoma sag is a broad, flat, little deformed downwarp that slopes very gently northward between the Zuni uplift on the west and the Lucero uplift and Puerco fault belt. McCartys syncline near the margin of the Zuni uplift forms the axis of the sag. Deposits at Ambrosia Lake line alone the northeastern corner of the Zuni uplift in the Chaco slope into the San Juan Basin. The Laguna depsoits lie along the eastern side of the Acoma sag.

The eastern and northeastern parts of the Zuni uplift are broken by numerous faults. Mapping by Thaden and Santos (1963) has more clearly delineated the pattern of these faults and in particular the San Rafael, San Mateo, and Ambrosia fault zones. As shown on Figure 1, the Ambrosia Lake area deposits are generally bounded by the San Mateo and Ambrosia fault zones.

The Zuni uplift and McCartys syncline together with the associated major faults and folds such as the Ambrosia anticline are considered to be Laramide. The Puerco fault belt is probably largely Pliocene, and its development considerably modified the eastern side of the Acoma sag during subsidence of the Rio Grande trough. Some faults that dislocate the volcanics capping Mesa Chivato around Mount Taylor may be late Pliocene or early Pleistocene.

Structures of most importance to ore localization consist of (1) fractures in the host sandstone; (2) folds in the Todilto Limestone; and (3) broad gently flexures of pre-Dakota age.

Both tectonic and gravity flow folds are present in the Todilto Limestone, and seem to have localized ore deposits in numerous places. The tectonic folds affect the adjacent formations and are in general larger than the minor disharmonic flow folds. As a consequence somewhat larger deposits may be found associated with the tectonic folds. The flow folds are intraformational and in many places range down to minute crenulations.

In the Ambrosia Lake and South Laguna areas most of the folds trend either northerly or westerly, and commonly follow the flanks and troughs of pre-Dakota folds. A second group of folds is late Jurassic or early Cretaceous and probably related to northward regional tilt of a broad east-west upwarp which extended across central New Mexico and Arizona during and following Morrison time.

About 300 collapse structures in the Bluff and Summerville formations have been mapped in the South Laguna area. They range up to 200 feet in diameter and from a few feet to possibly 300 feet in height. None of these South Laguna structures is known to penetrate into either the Morrison or the Todilto.

OCCURRENCES

The main host rocks for the ore bodies in the Grants districts are limestone and sandstone of continental origin. The deposits in the limestone are replacements and disseminations that form tabular to elongate bodies ranging from a few hundred to more than 200,000 tons. The deposits in the sandstone are grain coatings, interstitial fillings, replacements, and fracture coatings that form runs (Emmons, 1940) ranging from a few hundred to several million tons. A few deposits have been found in the Dakota carbonaceous shale as submicroscopic disseminations that form thin runs of only a few thousand tons. Although about 20 unranium minerals have been identified, coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$; uraninite, UO_2; tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}10H_2O$; and uraniferous carbonaceous material are predominant.

LIMESTONE DEPOSITS

Discoveries in the Todilto Limestone resulted in approximately 200 workable uranium deposits, varying considerably in size, all occurring within the major belt of of uranium mineralization that constitutes the Grants districts. Although these occurrences have provided the only appreciable production from a limestone host in the United States, it is relatively insignificant when compared to that from the Morrison sandstones. By the end of 1966 the limestone production amounted to about 4 percent of the total from the Grants districts.

The Todlito uranium deposits lie principally in two areas; those generally along the Todilto outcrop from the Haystack mine area to the F-33 mine (fig. 3), called the Todilto bench, and those in the South Laguna area. A few small deposits have been also mined in an area a few miles east of Grants.

The Todilto bench is transected by three fault sets; north-south, east-west, and N. 20° E. Displacements of the F-33 deposit indicate that the N. 20° E. set is postore.

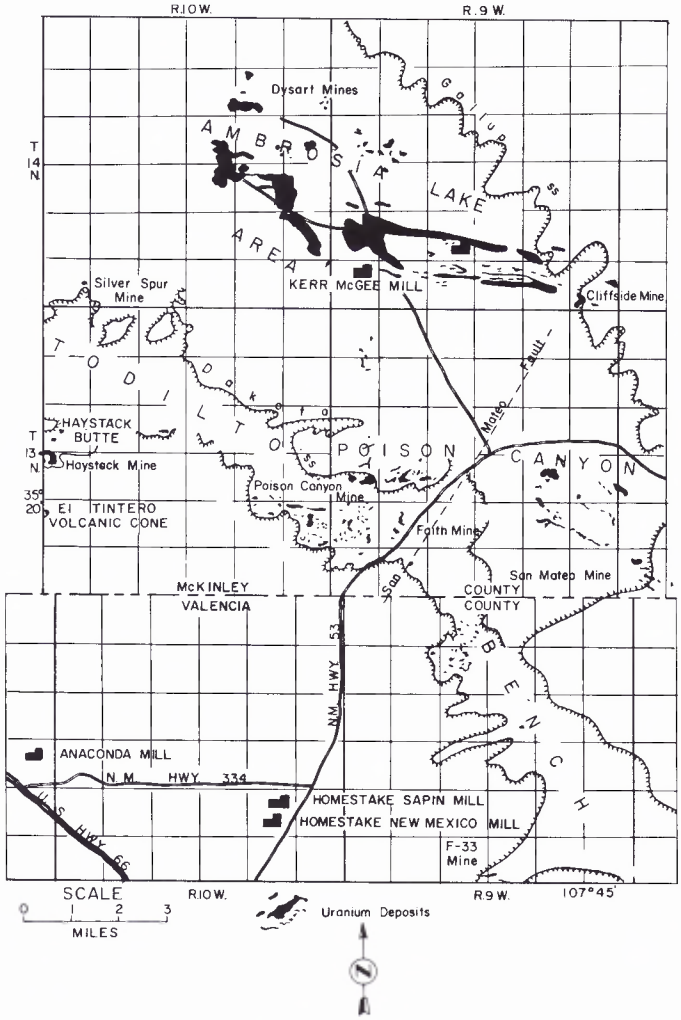


FIGURE 3.
Uranium deposits in the Grants district.

Folds in the Todilto are both harmonic and disharmonic with respect to the adjacent beds. The harmonic folds are part of the regional structure, and their distribution is incompletely known. The disharmonic intraformational consistently localized uranium deposits.
folds are small, irregular, and may be confined to any unit of the Todilto or lower Summerville. They vary from gentle arches to tight and recumbent forms. Considerable fracturing and occasional brecciation are associated with these intraformational folds. Both types of folds have

Very few of the Todilto uranium deposits have yielded more than 5,000 tons of ore. One exception that produced more than 100,000 tons of ore before its depletion in 1961 was the Haystack Mountain Development Company's open-pit mine in sec. 19, T. 13 N., R. 10 W. It was in a northwest-trending ore body about 1,150 feet long and 100 to 500 feet wide. The deposit was in a harmonic northwesterly plunging syncline, and the ore occurred chiefly in the platy member of the Todilto as disseminated yellow secondary uranium vanadates.

Another large deposit in secs. 33 and 34, T. 12 N., R. 9 W., has been worked from the underground F-33 mine. The ore body trends N. 70° E. for a developed distance of about 1,500 feet with an average width of about 70 feet. In the main ore zone the massive unit forms a bulbous lens immediately above the crinkly zone and is up to 20 feet thick. Most of the uranium is concentrated as uraninite in intraformational folds in this thickened lens of the massive unit. With the ore are very minor amounts of pyrite, fluorite, and barite. Some areas in the mine contain numerous solution channels and cavities in which the uranium vanadates, tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}10H_2O$ and carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$; the vanadium oxides; haggite, $V_2O_3 \cdot V_2O_4 \cdot 3H_2O$ and paramontroseite, V_2O_4; and the rare calcium vanadate, metahewettite have been deposited. Substantial reserves of uranium ore remain at the mine, where underground operations were suspended in 1959 because of the curtailment of the uranium market.

The Faith mine in sec. 29, T. 13 N., R. 9 W., has also produced more than 50,000 tons of uranium ore. Its shaft was sunk for Food Machinery Corporation to below the 450-foot level, where the ore was mined from a series of about 30 disconnected ore shoots that ranged up to 250 feet long, 60 feet wide, and 15 feet thick. Mining was terminated in 1963 when the ore was depleted. Most of the ore shoots were oriented northsouth along intraformational folds, but an abrupt change to an east-west orientation occurs in the extreme southern part of the trend. The largest ore shoot occurred on a broad intraformational fold upon which were several superimposed closed folds. The major uranium mineral was uraninite, and with it were gummite, fluorite, barite, pyrite, calcite, iron oxides, and manganese oxides.

Section 25, T. 13 N., R. 10 W., and section 30, T. 13 N., R. 9 W., together contain approximately one hundred uranium deposits that have produced more than two million pounds of U_3O_8 from both open-pit and underground operations. The individual deposits ranged considerably in size and shape but for the most part were small, and are now mined out. They comprised a few hundred to a few thousand tons of randomly oriented localizations of disseminated uraninite distributed in any or all of the limestone units. In the northern part of section 25, where some relatively large ore bodies occurred, an easterly trend is evident. In section 30 many of the relatively large ore bodies were oriented north-south. Apparent structural ore controls were chiefly intraformational folds and related joints. The supergene ore minerals included tyuyamunite, carnotite, gummite and uranophane, and calcite, pyrite, hematite, fluorite, and barite gangue.

Another area from which more than 50,000 tons of Todilto ore were produced is in secs. 4 and 9, T. 12 N., R. 9 W., where 50 small deposits, ranging in size up to 2,000 tons, were mined by open-pit methods and from adits driven into the walls of the pits. Control of the deposits by folds was often evident during mining. The ore occurred in all Todilto Limestone units and consisted mostly of uraninite in association with minor amounts of yellow uranium vanadates and uranophane, and with barite, calcite, fluorite, and iron oxides. Locally fluorite massively replaced the limestone.

The South Laguna area, about 30 miles east-southeast of Grants, comprises T. 8 N., R. 4 W., T. 8 and 9 N., R. 5 and 6 W., and the eastern part of T. 8 and 9 N., R. 7 W.; all of which is Laguna Pueblo land. The dominant structural features in the normally flat-lying beds of the South Laguna area are a series of broad and gentle pre-Dakota folds which trend both westerly and northerly across the general area. Innumerable small harmonic and intraformational Todilto folds are inconsistently oriented. In conjunction with joints they often exerted significant controls on the emplacement of the uranium mineralization. However, numerous intraformational folds are barren of uranium mineralization. Only a few faults of much displacement are known to occur in the South Laguna area; most of them are in the eastern half of T. 9 N., R. 5 W., and are oriented generally north-south. No relationship has been noted between faults and uranium mineralization.

Extending for about 15 miles from southwest corner of the area in a northeasterly direction is an outcrop zone of Todilto Limestone in which numerous radiometric anomalies were discovered in the mid-1950's by scintillation-equipment surveys and conventional foot prospecting. Although much close-spaced shallow drilling was done in the anomalous areas by The Anaconda Company, only two anomalous areas were sufficiently mineralized to warrant mining operations. One was the Crackpot mine near the center of the northwest quarter of sec. 8, T. 8 N., R. 5 W.; the other was the Sandy mine in the north-central part of sec. 27, T. 9 N., R. 5 W.

Nearly all Crackpot ore occurred in the crinkly and platy zones of the Todilto; the upper massive unit was virtually barren of uranium. Intraformational folds were the chief ore control. The minerals consisted mainly of uraninite and yellow uranium vanadates that were irregularly disseminated in a small fold. Accessory minerals other than calcite and limonite were not in evidence.

The Sandy deposit consisted of several small pods in Todilto Limestone and upper bleached Entrada Sandstone on a gentle south-facing moncline. Several small harmonic and intraformational folds provided some ore control, but the ore cutting across the tilted Todilto-Entrada contact indicated that folds were not the only control. The ore was similar mineralogically to that in the Crackpot deposit. Less than 5,000 tons of ore were produced from the Sandy and Crackpot open-pit mines, and no ore has been produced from either mine since 1955.

SANDSTONE DEPOSITS

Uranium deposits have been found in the Entrada Sandstone, Morrison Formation, and the Dakota Sandstone, in addition to the Todilto Limestone. The deposits in the Morrison are by far the largest and most continuous known to date, while those in the Entrada and Dakota are small, isolated, and widely scattered.

Entrada Sandstone

Deposits in the Entrada occur just below the Todilto Limestone contact in the bleached part of the upper sandy member. This member is 80 to 250 feet thick, reddish orange to light-gray, moderately well-cemented and well-sorted fine- to medium-grained quartz sandstone. The upper 5 to 30 feet is generally bleached to light gray; this is thought to be the result of weathering of the pre-Todilto surface.

The principal Entrada uranium deposits were at the Haystack mine (sec. 19, T. 13 N., R. 10 W.), the Zia mine (sec. 15, T. 12 N., R. 9 W.), and the Sandy mine (sec. 27, T. 9 N., R. 5 W.) in the South Laguna area. These and all other known deposits in the districts appear to be supergene occurrences derived from overlying Todilto ore bodies. Field observations of the present terrain indicate that the overlying impermeable formations were eroded away making it possible for meteoric waters to reach the Todilto, and tension fractures associated with ore-localizing intraformational folds provided the permeability necessary to allow the waters to leach the uranium from the limestone. The uranium was reprecipitated in the Entrada in the form of uraninite, coffinite, and tyuyamunite.

Morrison Formation

More than 95 percent of the uranium ore produced in the Grants districts has been mined from the Westwater Canyon and Brushy Basin members. The Westwater Canyon is the principal host rock west of Mount Taylor in the Ambrosia Lake, Smith Lake, Churchrock, and Poison Canyon areas. In the Laguna district the Jackpile sandstone is the principal host.

Special terms are in use locally to describe recognizable variations in the occurrences of black Westwater deposits west of Mount Taylor.

OLDER ORES	YOUNGER ORES
prefault	postfault
trend	redistributed
primary	secondary
roll	stack

The term stack is intended to refer to thick postfault, redistributed occurrence, but the superposition of two or more runs has the appearance of, and is sometimes erroneously termed, a stack.

Prefault or trend ore bodies are properly termed runs. They are usually elongate in a west-northwesterly direction. In the lower Westwater, they are generally a part of a larger, elongate, thin layer of mineralization in which the grade, thickness, and width of mineralization have been observed to increase at predictable intervals into runs.

In places the ore changes elevation abruptly, crosses the bedding, and thickens to form a roll. It has been observed that when this change in elevation occurs across the west-northewesterly trend direction, the higher elevation is consistently to the north and up-section.

In the upper Westwater the mineralization is not as wide-spread, and the deposit generally forms a single wide run that is lenticular in cross section, and may have small satellitic prefault ore bodies along its north and south edges. Here again the northern ore bodies have a higher stratigraphic elevation than those to the south, although the regional dip is northward.

A direct relationship has not been established between prefault ores and specific structural features. Faults observed in the older ore bodies throughout the district indicate post-ore movement inasmuch as the ore and bedding planes are displaced the same amount. An indirect relationship exists between the uranium deposits and regional deformation which controlled the original linear features in the Morrison sandstone host beds.

Redistributed or postfault uranium deposits are generally associated with, and quite often engulf, an older prefault deposit. These deposits tend to be more equidimensional horizontally and considerably thicker (up to 100 feet) than the prefault occurrences. Their direction of elongation is commonly related to an increase in fracture density along which the redistribution has taken place. Changes in grain size and sorting, intraformational mudstone layers, gouge in fault zones, and the amount of fracturing are all features that have influenced the shape, position, and grade of the redistributed deposits.

The redistributioan process, which has apparently been in progress since the earliest Laramide tectonic activity, changed the hydrodynamics and set formation waters in motion. Redistribution is accomplished by circulation of aerated ground water through an area of older mineralization. These solutions change the uranium from a plus four to a plus six valence state that can form complexes with bicarbonate and sulfate ions present in the waters. These uranium-rich solutions proceed down dip until their oxidizing capability lessens to the point where precipitation takes place in a favorable (reducing) environment.

Oxidation, solution, and reprecipitation are well illustrated by the presence of high-grade redistributed ore in a zone along the contact between oxidized and unoxidizd sandstone. From this contact zone the grade decreases and finally feathers out into the unoxidized sandstone. Remnants of prefault ore that may have provided the uranium

for redistribution have been observed in oxidized sandstone through which redistributing solutions have passed.

The uranium minerals that make up the deposits have been chemically precipitated as sand grain coatings, interstitial cement, fracture fillings, and replacements of carbonaceous material. The minute grain size makes megascopic mineral identification nearly impossible and microscopic study difficult. The most reliable identifications have been made using X-ray equipment.

Coffinite, uraninite, and uraniferous carbonaceous material are the principal uranium-bearing materials found throughout the districts in the unoxidized sandstone deposits. Granger (1963) describes the carbonaceous material as . . ." an authigenic organic matter that seems to have introduced in a fluid state and has remained as a precipitate or residue to form grain coatings, interstitial cement, and fracture fillings". It is coextensive with prefault ore and seems to be the matrix or gangue in which many of the prefault ore metals occur. Carbonaceous material in the sandstone host is generally uraniferous and contains coffinite, but where it is oxidized, such as in shallow deposits exposed at the surface, the coffinite may be destroyed and the uranium leached. Coalified fossil trunks, limbs, and fragments of wood and grasses may also be uranium-bearing. Numerous uranium-bearing dinosaur bones have been found in the Morrison.

The most common secondary minerals are tyuyamunite, metatuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$, and carnotite. Zippeite, $2UO_3 \cdot SO_3 \cdot 5H_2O$, andersonite, $Na_2Ca(UO_2)(CO_3)_3 \cdot 6H_2O$, and bayleyite, $Mg_2(UO_2)(CO_2)_2 \cdot 18H_2O$, are commonly found as post-mining efflorescent deposits on the mine walls.

Commonly occurring interstitial gangue minerals are pyrite, marcasite, calcite, jordisite, ilsemannite, and ferroselite ($FeSe_2$). Native selenium, barite, calcite, and pyrite occur as fracture fillings, and pascoite is a common post-mining efflorescent occurrence.

Molybdenum in the mineral jordisite, MoS_2, is a common accessory in both the upper and lower deposits where it is found as a halo or fringe on the edges as well as within the ore. The mineral montroseite is also an included accessory mineral.

The most significant deposits in the Westwater Canyon Member are found in T. 14 N., R. 9 and 10 W. (the Ambrosia Lake area). The minable uranium ore bodies (those containing more than two pounds of U_3O_8 per ton) form a nearly continuous west-northewesterly striking deposit that extends some eight miles from the southeast corner of T. 14 N., R. 9 W. to the northeast quarter of T. 14 N., R. 10 W. along the southern edge of the Ambrosia Lake trend these deposits occur throughout the entire thickness of the member, including the "Poison Canyon" tongue. Santos (1963) noted that this stratigraphic range gradually lessens to the north as follows: "Through the center of the belt, ore deposits occur from near the middle to the top of the Westwater Canyon, and along the northern margin of the belt, they occur at the top only."

The subdivision of the 250-foot thick Westwater into distinguishable sandstone units, separated by discontinuous mudstone layers and beds, has been a practical necessity for correlating the ore bodies. These ore-bearing units range in thickness from 12 to 60 feet, and the ore ranges in thickness from less than two feet in runs to more than 100 feet in redistributed stacks.

The localization of the uranium deposits within the various sandstone units occurred in at least two phases. The first deposition occurred in reducing environments created when areas of dense vegetation were rapidly buried and later converted into carbonaceous material. During this time sedimentary features controlling porosity and permeability had their most important effect. Interstitial and interbedded mudstones controlled the flow of and trapped the carbonaceous fluids and uranium-bearing solutions. Large areas of unoxidized clean sandstone that contain little interstitial mudstone are barren even though geologic evidence indicates that uranium-bearing solutions passed through the sandstones.

The second and posssible succeeding phase of localization occurred when the uranium in older prefault runs was redistributed by moving ground waters. The effectiveness of the redistribution process along zones of increased permeability is well demonstrated in the Poison Canyon trend where prefault uranium deposits in the San Mateo fault zone and associated syncline were completely removed and were probably reprecipitated down dip to form the Hogan and the Cliffside deposits.

The permeability that allowed deposits to be destroyed was also necessary for the formation of the characteristic Ambrosia Lake stack ore bodies. Examples of stack ore bodies that have been localized in fault zones and areas of increased fracture density are found in secs. 10, 11, 22, 23, 24, and 25, T. 14 N., R. 10 W., and secs. 29, 30, 35 and 36, T. 14 N., R. 9 W. Carbonaceous material is generally present but less abundant in redistributed deposits.

Production from individual Ambrosia Lake mines has ranged from less than 100 tons to more than 1,000 tons per day. At the end of 1966 production from the larger mines averaged about 600 tons per day, but with an expanding market in sight production is increasing accordingly.

The first discoveries in the Westwater were made in runs that form the "Poison Canyon ore trend". The occurrences in this trend also span some eight miles from the Blue Peak mine (sec. 24, T. 13 N., R. 10 W.) where uranium ore occurs at the surface, southeasterly to the San Mateo mine, where ore lies at a depth of about 1,400 feet (fig. 3).

Most of the ore occurs in typical upper Westwater runs that are found where "Poison Canyon" sandstone exceeds 40 feet in thickness. Although most of the ore is localized near the base of the unit, the changes in thickness do not reflect channeling or thickening at the base, but are the result of the accumulation of stray sandstone lenses at the top of the unit (Rapaport, 1963).

The southern edge of the "Poison Canyon" trend is marked by a straight sharp boundary between ore and barren rock that more or less parallels the long axis of the sandstone lenses. In comparison the northern edge is irregular, and the transition from ore to waste is gradual;

this irregularity is the result of redistribution down dip along northeasterly striking fracture systems. Uranium in the ore bodies in secs. 7 and 8, T. 13 N., R. 9 W., was almost certainly dissolved from runs in the trend and carried more than 2 miles down dip along a fault system before being redeposited. The San Mateo fault zone is an area where removal of pre-existing ore bodies was complete.

All production from the "Poison Canyon" trend has been from underground mines except for that from the rim at the Blue Peak mine, and from the Poison Canyon open pit. Daily production from individual mines along the trend varied from a few tons to several hundred tons.

The Smith Lake area is about 20 miles north-northwest of Ambrosia Lake in T. 15 N., R. 13 W., (fig. 1). The Homestake-Sapin Partners' Black Jack No. 1 and No. 2 mines are the only producers and deposits in this area.

The Black Jack No. 1 deposit, in sec. 12, T. 15 N., R. 13 W., is a J-shaped easterly trending ore body that hooks south and west, and lies on the east end of the Mariano Lake anticline. This ore deposit of more than one million tons occurs in the middle and upper Westwater, in seven zones (Fitch, 1961). The lower three intertongue and form an east-west prefault run nearly 3,600 feet long. The upper four zones appear to be redistributed deposits that have formed in areas of increased fracture density along both normal dip-slip and strike-slip faults (McRae, 1963). Shorter northeasterly prefault runs that have been partly removed are found in the southern part of the deposit. In this ore body, the sharp ore-waste cutoff occurs along the north edge of the run. The reason for the apparent redistribution from north to south is not clear. The mine has produced more than 1,000 tons per day and now averages about 750 tons per day.

The Black Jack No. 2 deposit was in the north-central part of sec. 18, T. 15 N., R. 13 W., (fig. 1), at the southwest end of the Mariano Lake anticline. It occurred in the "Poison Canyon tongue" of the Westwater Sandstone. This sandstone lens is a very local occurrence and ranges in thickness from 18 to 60 feet in the mine area. More than 200,000 tons of ore were produced from the deposit before it was mined out in 1964. Daily production ranged from 100 to 200 tons. There were three zones of ore; the lowermost zone near the base of the sandstone was the most prevalent. Observations in the mine indicate that the ore was prefault and deposited in a sand-filled channel where shapes of the ore pods were controlled by changes in permeability related to interbedded mudstone.

The westernmost Westwater occurrences have been found in T. 15, 16, and 17 N., R. 16 W., in the Churchrock area (fig. 1). Ore production from the area has been limited. A few small mines along the rim produced a few thousand tons each, and the Churchrock mine operated by United Nuclear Corporation produced less than 50,000 tons from the Westwater before it was closed. A substantial tonnage of low-grade reserves remains.

In the Churchrock area uranium mineralization has been found throughout the Westwater, with the bulk occurring in the middle of the member. Deposition and apparently later leaching of the deposit occurred along a northeasterly striking fracture zone. Natural radioactivity logs of widely spaced drill holes in the above-mentioned three townships indicate that uranium-carrying solutions ranged widely in the Churchrock area.

A new deposit has been discovered north-northeast of the Churchrock mine, and several drills are presently being employed by local operators to develop it. Drill holes in this Northeast Churchrock deposit have cut minable thicknesses of ore grade mineralization throughout the member. The best concentrations are near the base and in the upper part of the member. The configuration of the deposit suggests that the lower ores are prefault and the upper ores redistributed.

The North Laguna area is about 30 miles east of Grants and includes the Jackpile, Paguate (pronounced Pah wah' tee), St. Anthony, L-Bar, and Woodrow ore bodies (fig. 4). The Jackpile and Woodrow deposits were discovered in November, 1951, with airborne scintillation equipment; an outcrop of the St. Anthony deposit was discovered in early 1954, and the Paguate and L-Bar deposits, neither of which are exposed at the surface, were discovered in 1956 as a result of systematic exploration drilling.

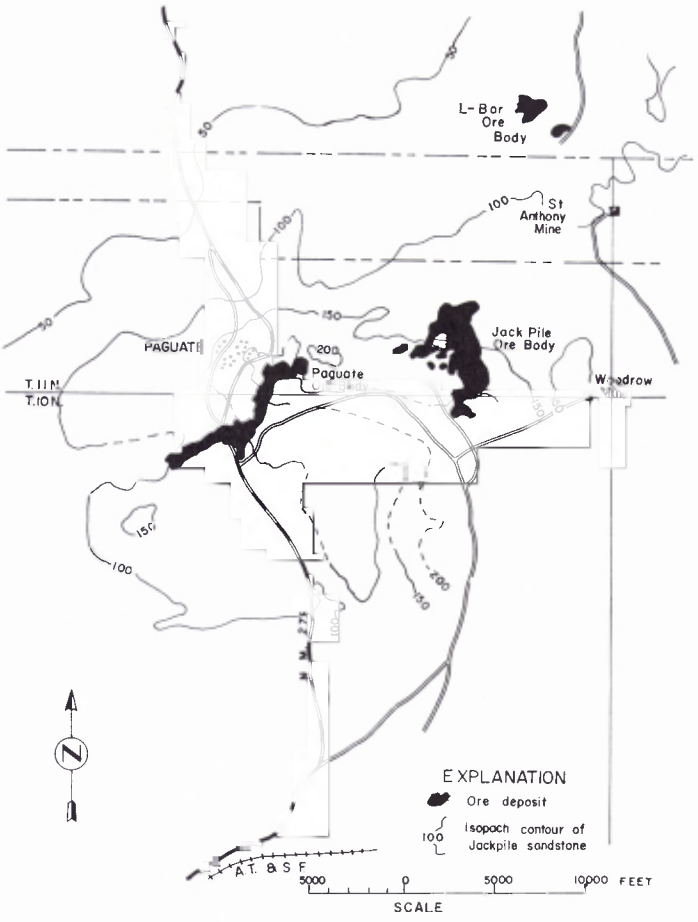


FIGURE 4.

North Laguna area, showing the relationship of the ore bodies to Jackpile sandstone thicknesses.

The Jackpile sandstone is the host rock for all economically important uranium deposits in the North Laguna area. It is thought that this unit was derived from the southwest; it was deposited in a northeasterly-trending downwarp known to be at least 35 miles long, 15 miles wide, and 220 feet deep. The Jackpile and Paguate ore bodies are in the thicker part of the Jackpile sandstone.

There are practically no faults in the area, and those that are present are small and have no apparent control over primary ore localization. Mineralization was influenced in different degrees by such controlling factors as cross-bedding, carbonaceous material, mudstone layers and lenses, bedding planes, lithologic changes, weak intraformational faults, and thickness of host rock.

The Jackpile deposit has a known length of about 1.5 miles, and an average width of about one-half mile. The Paguate deposit has a known length of over 2 miles and an average width of a few hundred feet. In the Jackpile mine nearly all the uranium mineralization occurs in the lower half of the host sandstone. The ore ranges in thickness from 20 to 50 feet and is locally separated by various thickness of barren sandstone of similar lithology. Uranium mineralization in the eastern part of the Paguate deposit normally occurs in the upper one-third of the Jackpile sandstone; locally, mineralized lenses have been truncated by the overlying Dakota Sandstone. In the western part of the deposit ore normally occurs in the lower two-thirds of the host sandstone. To date the following minerals from the Jackpile and Paguant mines have been identified:

Autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 10\text{-}12H_2O$
Becquerelite, $7UO_3 \cdot 11H_2O$
Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$
Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$
Hydrogen-autunite, $HUO_2PO_4 \cdot 4H_2O$
Metatorbernite, $Cu(UO_2)_2(PO_4)_2 \cdot {}_nH_2O_n = 4$ to 8.
Metatyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}7H_2O$
Phosphuranylite, Ca. $(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$
Schoepite, $4UO_3 \cdot 9H_2O$
Sklodowskite, $Mg(UO_2)_2(SiO_3)_2(OH)_2 \cdot 6H_2O$
Soddyite, $(UO_2)_5(SiO_4)_2(OH)_2 \cdot 5H_2O$
Tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}10H_2O$
Uraninite, UO_2
Uranophane, $Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$

Noncommercial quantities of selenium, molybdenum, and vanadium also occur in association with the uranium. Metallurgical studies show the normal mill feed from the Jackpile and Paguate deposits to be about as follows:

Black orxidized uranium complexes	80%
Uraninite	15%
Black organo-uranium complexes	3%
Coffinite	2%

Coffinite and uraninite are relatively more abundant in the high-grade ores. The uranium minerals are intimately mixed with and replace carbonaceous material, or occur as the cement in the sandstone.

Production from the Jackpile and Paguate mines averaged more than 4,000 tons per day prior to May, 1959, when the AEC curtailed its purchases of uranium concentrate. Since then production has been reduced to about 950 tons per day, but it is anticipated that it will soon increase as market demands increase.

The St. Anthony deposit is about two miles northeast of the Jackpile mine. It occurred in the Jackpile sandstone and was mined from the 250 level of a vertical shaft by Climax Uranium (a subsidiary of Climax Molybdenum) during the period 1957-60. The ore body was about 1000 feet long, 50 to 300 feet wide, and up to 30 feet thick. The mineralogy of the deposit was essentially the same as that of the Jackpile and Paguate ore bodies, being for the most part a complex of black uranium oxides in which the higher grade portions comprised coffinite to a large extent, with some associated uraninite. Normal production amounted to somewhat less than 200 tons per day of ore with a grade of about 0.20 per cent U_3O_8, most of it mined by a pillar-retreat stoping.

The L-Bar deposit is a partially developed ore body located about a mile northwest of the St. Anthony deposit on land belonging to the L-Bar Cattle Company. Its shape as developed to date is roughly a square about 2,000 feet on a side, but drill-hole data indicate that the mineralization may extend for another 2,000 feet southeasterly. The deposit is made up of numerous, fairly discontinuous thin lenses of uranium mineralization that occur throughout the entire section of Jackpile sandstone. The ore composition is the same as that found in the Jackpile and Paguate mines.

The Woodrow mine is about a mile east of the Jackpile mine. The deposit occurred in a nearly vertical breccia pipe of Jackpile sandstone. the pipe is for the most part bounded by strong ring faults that penetrate into Brushy Basin mudstone near the surface, and which continue downward into the Morrison Formation beyond a known depth of 272 feet. The core of the pipe has been downthrown approximately 40 feet, and relatively thick, black clay-gouge was formed along the fault. Most of the mineralization occurred in this core, and in the interval from 31 to 51 feet below the surface small quantities of ore assaying as high as 20 per cent U_3O_8 were found. In this same interval of depth the mineralization extended up to 10 feet outside the ring fault, along minor fractures. (Wylie, 1963). The following minerals have been identified from the Woodrow pipe:

*Autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 10\text{-}12H_2O$
Barite, $BaSO_4$
*Becquerelite, $7UO_3 \cdot 11H_2O$
Chalcopyrite, $CuFeS_2$
Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$
Galena, PbS
Jarosite, $KFe_3(OH)_6(SO_4)_2$
Johannite, $Cu(UO_2)_2(SO_4)_2(OH)_2 \cdot 6H_2O$
Marcasite, FeS_2
*Meta-autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 8H_2O$
*Metatorbernite, $Cu(UO_2)_2(PO_4)_2 \cdot nH_2O_n = 4$ to 8
*Pyrite, FeS_2
Sabugalite, $HA1(UO_2)_4(PO_4)_4 \cdot 16H_2O$
Torbernite, $Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$

* known to occur also in the Jackpile deposit.

*Uraninite, UO_2
Uranopilite, $(UO_2)_6(SO_4)(OH)_{10}\cdot 12H_2O$
*Zippeite, $2UO_3\cdot SO_3\cdot 5H_2O$

The Woodrow pipe is without question a unique uranium host that has certain geologic characteristics otherwise unknown except at the Orphan pipe on the south rim of the Grand Canyon. The strong ring faults, the breccia, and sulfides suggest that the mineralization in the pipe may be hydrothermal.

The Woodrow deposit was mined from the 100-foot level to the surface in 1954, and from the 200-foot to the 100-foot level in 1956. The first mining phase produced ore with an average grade of 1.53 per cent U_3O_8 and 0.05 per cent V_2O_5, whereas the second phase produced ore with an average grade of 0.32 per cent U_3O_8 and 0.03 per cent V_2O_5.

Dakota Sandstone

Uranium occurs in basal interbedded sandstones and shales of the Dakota. The deposits have been found in the Gallup area along the hogback formed by the Nutria monocline, in the Churchrock area, and in the southwestern corner of the Ambrosia Lake area. The first mine in the Dakota Sandstone and one of the first in the district was the small open-pit Silver Spur mine in sec. 31, T. 14 N., R 10 W. fig. 3). The largest producers, about 40,000 tons each, have been the Diamond No. 2 mine south of U.S. Highway 66 on the Nutria monocline (fig. 1) and the Dakota level of the Churchrock mine. At the end of 1966 the Diamond No. 2 was still producing a few hundred tons per month and was the only Dakota deposit being worked. The total production from the Dakota deposits has been about 100,000 tons containing four pounds of U_3O_8 per ton.

The uranium has been concentrated in fine- to coarse-grained sandstone and interbedded carbonaceous shale that in places contain enough carbonized vegetal remains to form thick peat beds. The Hogback No. 4 deposits occurred entirely within a shaly carbonaceous bed.

Primary uranium minerals, uraninite and coffinite, are found in deposits that lie below the water table. On the outcrop and in near surface deposits these have been oxidized to form carnotite and other secondary minerals. These primary and secondary minerals impregnate the host rock as sand grain coatings and interstitial fillings, and the secondary minerals commonly fill fractures.

The deposits are nearly equidimensional in the horizontal plane, and their thickness has been limited to less than 20 feet by the thickness of the sandstone units in which they occur. The elongation of the deposits generally is parallel to northerly trending fractures associated with the ore bodies.

The occurrence of several of the ore bodies in folded, faulted, and fractured areas suggests that the uranium in the Dakota deposits may be post-Laramide and has been derived from eroded updip or underlying Morrison deposits and redistributed along the fractures where the favorable carbonaceous environment was encountered.

* known to occur also in the Jackpile deposit.

ORIGIN

Theories of the origin of the Grants deposits, as with most others of the Colorado Plateau, have fallen into the following genetic types:

(1) Syngenetic-sandstone, mudstone, tuff, carbonaceous shale
(2) Ground water
  (a) Lateral secretions
  (b) Supergene
(3) Hydrothermal

Some theories are combinations of the above or are multiple variations of one of them, such as a penesyngenetic category. To evaluate the genesis of the deposits properly it is absolutely essential to know as nearly as possible the geologic history beginning with the source and deposition of the sedimentary materials. It is therefore fitting to begin with the nature and source of the Morrison beds.

The Morrison sediments are markedly tuffaceous and clearly indicate a volcanic provenance in which there may have been flow, pyroclastic, geyser, and hot spring eruptions. Significant quantities of uranium may have been associated with these eruptions. If this were true the uranium could have been brought to the sites of the Morrison deposition by surface and subsurface waters, fluvial debris, and fallout. The surface and subsurface waters moving toward the Morrison depositional sites could have continued to extract uranium from unstable rock debris during transportation. Associated with the rocky sediment was also considerable organic debris or trash which accumulated in irregular deposits that eventually became instrumental in localizing many of the ore deposits. Diagenetic redistribution of uranium may have continued during burial, compaction and cementation. These were the conditions and environments during the earliest stage of possible uranium accumulation by sedimentary syngenetic or pensyngenetic processes.

The sedimentary stage of late Jurassic was brought to a halt in most of the area by the rise of the Mogollon highland with its broad gentle tilt to the north (Kelley, 1955). Some gentle folding accompanied the tilting while widespread stripping reworked the upper sediments to the north. Channel sands such as the Jackpile and other post Brushy Basin deposits farther to the north may have formed during this episode. Water tables, ground-water dynamics, and water chemistry were undoubtedly modified considerably during this rejuvenaion. Previous uranium deposits could have been weathered, leached, eroded mechanically, and redeposited several times. To many geologist this has been a favored time for formation of the older runs west of Mount Taylor and the Jackpile and Paguate deposits.

This second state was terminated with marine encroachments which accompanied regional subsidence of subcontinental dimensions and eventually buried the Grants region to nearly 5,000 feet in late Cretaceous and possibly 7,000 by Paleocene time. Although temperatures and pressures were increased during this stage, ground-water

circulation essentially ceased and modifications of deposits would have been local and slight.

The next stage of potential ore formation began with Laramide deformation and continued through the Tertiary. For the Grants region the rise of the Zuni uplift and the subsidence of the San Juan Basin and its subsidiary Gallup and Acoma embayments were the predominating tectonic influences. In addition to the Zuni dome all the folds and most of the faults that are so prevalent in the vicinity of Ambrosia Lake were formed during this time. Metallizing porphyry intrusions may have occurred at this time in the more than 300 square mile area between Ambrosia Lake and Laguna that is covered by the Mount Taylor volcanic field. The obvious effects upon the deposits beyond deformation included general decline of pressure and temperature and increased mobility of the ground water. Additionally, hydrothermal alteration and introduction of uranium is a possibility at this stage.

Continued regional uplift probably resulted in first reexposure of the Morrison along the Zuni uplift by middle Tertiary. By the end of the period the uranium-bearing horizons had been stripped and truncated well off the crest of the uplift where the Precambrian was exposed in a wide erosion surface. During all this time and into the present, oxidation and solution by meteoric water progressively modified and "worked" the deposits down dip, to their present positions, especially to the north and northeast of the uplift. Some of this downward migration of the uranium-bearing solutions is thought also to have crossed the formations downard to be precipitated in the Todilto Limestone.

The history of exposure and modification at Laguna was quite different, as these great deposits lay in the Acoma embayment well removed from the energizing effects of the Zuni uplift. Exposure came later, slower, and along a much broader area owing to the low dips. As a result supergene buildup was not shifted so much down the dip as in the redistributed stacks which characterize the Ambrosia Lake and Gallup areas.

The foregoing outline of the geologic history since late Jurassic furnishes a framework of conditions which must have controlled the formation of the deposits regardless of the specifics of their origin. The source of the metal, whether from sedimentary debris, ground-water introductions, or hydrothermal additions is the principal genetic problem along with timing of deposition.

In order to decide upon these problems, petrographic, spectrographic, paragenetic, geochemical, isotopic, and radiometric studies are pursued. These appear to raise additional subsidiary problems such as the chemistry of the transporting fluids, precipitation or concentration, the significance of the widespread alteration in the Morrison sands, etc. Nevertheless, some conclusions appear to have reached near unanimity. One of these is recognition at Ambrosia Lake of two stages (prefault and postfault) of ore body development associated with down dip oxidation, solution, and enrichment. If an early derivation of the ore deposits is agreed upon, then later modification and redistribution energized by the Laramide disturbances and erosion, become more or less logical, corollary, sequential steps that would accompany the known geologic history.

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