37. Geology and Exploitation of Uranium Deposits in the Lisbon Valley Area, Utah

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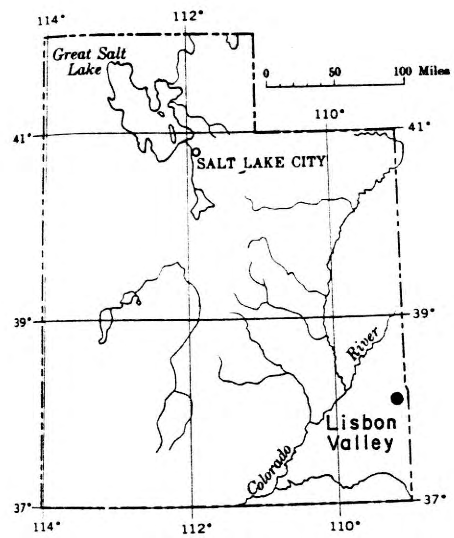
* U.S. Atomic Energy Commission, Grand Junction, Colo.



ABSTRACT

Uranium ore deposits in the Lisbon Valley area are in an arcuate belt, 15 miles long by one-half-mile wide, on the southwest flank of the Lisbon Valley anticline. They range in size from 500 to 1,500,000 tons and by mid-1965 had yielded 6,147,000 tons containing 48,530,000 pounds of U_3O_8. Ore bodies average 6 feet thick, are tabular, amoeba-shaped masses, concordant to the bedding, and are in the thickest, lowest sandstone unit of the Moss Back Member of the Chinle Formation of Triassic age. The host rock is predominantly a fluviatile, calcareous, fine-grained to conglomeratic sandstone. Uraninite, the principal ore mineral, fills the pores in the sandstone and partly replaces sand grains and fossil wood fragments.

During Late Permian and Early Triassic time pre-Chinle Formations were arched to form the ancestral Permian anticline. Moss Back streams truncated Moenkopi and Cutler beds which capped the ancestral anticline and then covered it with fluviatile clastics, which were subsequently covered by thousands of feet of Triassic, Jurassic, and Cretaceous sediments. Uranium, probably derived from the Chinle Formation by diagenetic processes, was transported in connate ground waters, was moved by compaction or hydrostatic forces, and was deposited under reducing conditions. Uranium was emplaced around the crest of the ancestral anticline, prior to the Laramide orogeny. During the orogeny, the Tertiary-Lisbon valley anticline was superinduced on the Permian anticline and, penecontemporaneous with uplift, was faulted parallel to its longitudinal axis. The Big Indian ore belt on the southwest flank footwall block was elevated to approximately its present position, and the northeast flank hanging wall block was elevated only slightly.

An extension of the Big Indian ore belt around the northeast flank of the ancestral Permian anticline may exist in the Moss Back sandstone in the downthrown block northeast of the Lisbon Valley fault.

INTRODUCTION

This paper reviews the exploration and mining of the uranium deposits in the Big Indian ore belt and discusses the geology important to the deposits. The ore belt is on the southwest flank of the Lisbon Valley anticline, near the center of the Colorado Plateau (Figure 1 and see Fischer Figure 1, this volume), and is about 40 miles southeast of Moab, Utah.

The ore deposits described herein are in the Moss Back Member of the Chinle Formation of Triassic age. The uranium-vanadium deposits in the Salt Wash Member of the Morrison Formation of Jurassic age at the northwest end of the Lisbon Valley anticline and also in Dry Valley south of the anticline and the copper deposits in the Dakota Group sandstone beds of Cretaceous age along the Lisbon Valley fault are not described in this paper (Figure 1).

Geologists and mine operators of Atlas Corporation, Homestake Mining Company, Standard Metals Corporation, Utex Exploration Company, Continental Materials Corporation, and Humeca Exploration Company have supplied mine maps, drill hole logs, and some geologic maps, without which this study would not have been possible. Information on mining methods and cost was supplied by Lochinvar B. Birch of the U.S. Atomic Energy Commission. Critical reviews and constructive suggestions by R. P. Fischer of the United States Geological Survey and by R. A. Laverty of the United States Atomic Energy Commission were very helpful. Unpublished geologic reports on the Big Indian mining district, prepared prior to 1958, by M. A. Lekas, N. E. Salo, John Volgamore, P. L. Grubaugh, and Robert Schoen, all former U.S. Atomic Energy Commission geologists, were used extensively for back-up information.

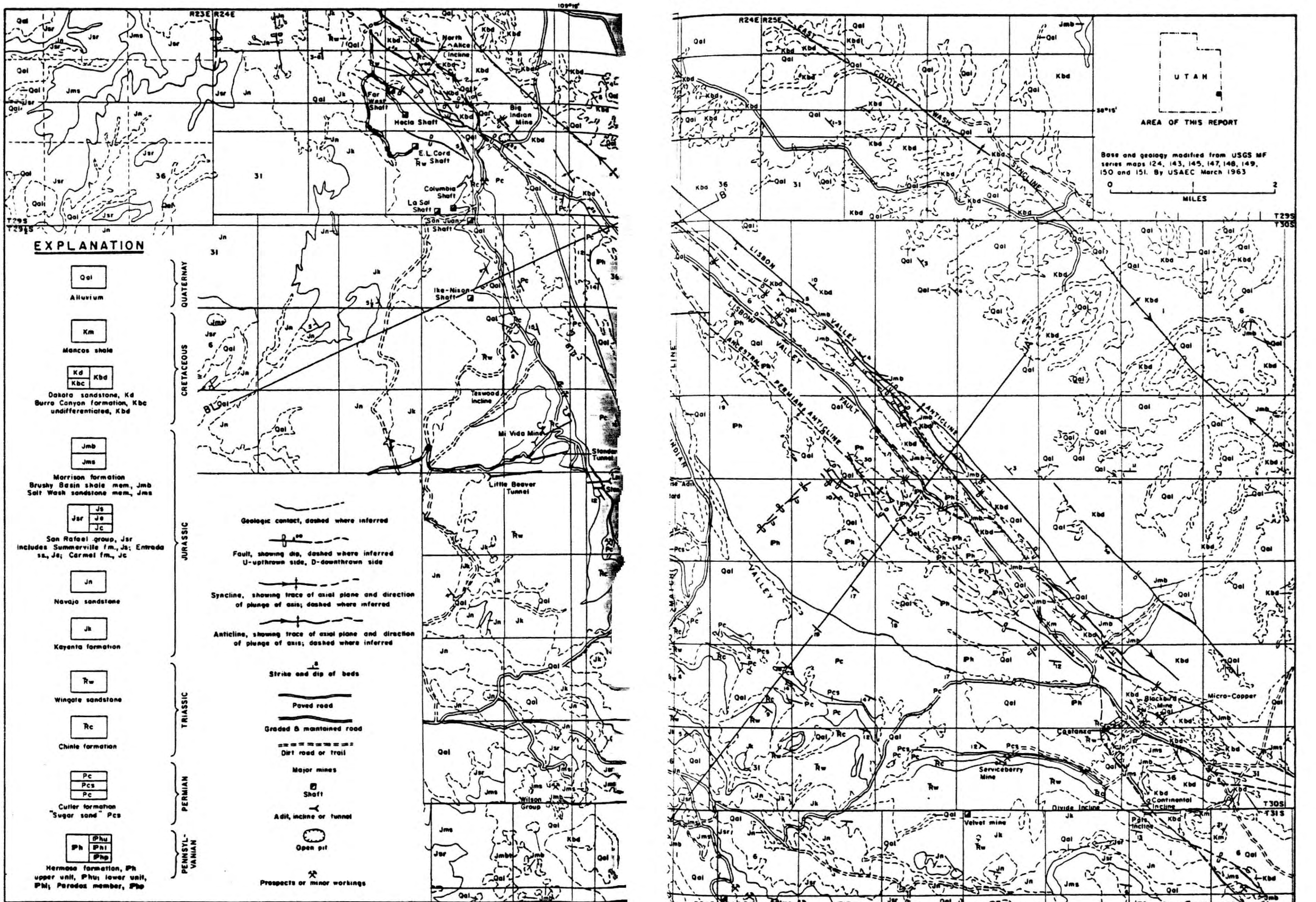


FIG. 1. *Geologic Map of Lisbon Valley Area, San Juan County, Utah.*

EXPLORATION AND MINING HISTORY

Exploration History and Costs

The first discovery of uranium-vanadium ore on the Lisbon Valley anticline was made in 1913, at the south end of the anticline, on outcrops of basal Chinle sandstone. In 1948, low-grade uranium deposits were discovered and developed in upper Cutler sandstone outcrops along the center of the southwest flank of the anticline. These were the deposits that attracted Charles Steen to the area. In July 1952, Steen drilled the famous 70-foot deep discovery hole on the Mi Vida claim just off the Big Buck claims and down dip from the mines in the Cutler Formation. He encountered about 13 feet of uraninite ore in the Moss Back sandstones, about 100 feet higher stratigraphically than anticipated (1, p. 5) (2, p. 1). Following this discovery, claim staking and exploration drilling progressed rapidly to the northwest and southeast and continued with intensity through 1956. During this ensuing period, the following deposits in the Chinle were discovered by drilling in the north half of the Big Indian ore belt: Standard (Big Buck), Little Beaver, Louise, Texwood-Stinko, Ike-Nixon, La Sal, Columbia, San Juan, Cord (Jen), Radon (Hecla), Far West, and North Alice (Figure 2). A peak in exploration was reached in 1955, when 647,000 feet of drilling was reported. By mid-1956, exploration drilling began to taper off. By the end of 1964, over 4500 holes totalling about 2,200,000 feet had been drilled in the search for uranium on the anticline, and over 3000 holes, spaced 200 to 500 feet apart, had been drilled within the delineated ore belt (Figure 2). This intensity of drilling argues against the existence of any undiscovered large ore deposits in the drilled areas, although a number of small ore deposits may remain undiscovered.

The discovery in 1962 and the mining of uranium ore in 1964 at the Costanza mine (Figure 1) in sections 26 and 35, T30S, R25E established the existence of uranium ore on the northeast side of a hinge fault that has more than 2000 feet of displacement. This high angle fault is one of the main bifurcating faults at the south end of the Lisbon Valley fault. Between May 1964 and July 1965, Humeca Exploration Company drilled five deep holes (2500 feet ±), in the center of section 21, and in the southwest corner of section 22, T29S, R24E. Interpretation of Century Geophysical Company gamma ray logs of these holes indicated that two holes penetrated up to 33 feet of Moss Back sandstone and 2 to 8 feet of uranium ore. This discovery established the occurrence of uranium ore in the downthrown block northeast of the main Lisbon Valley fault at the north end of the anticline.

Present direct drilling costs in the district are about \$1.00 to \$1.25 per foot for non-core rotary drilling and about \$5.00 per foot for core drilling to depths of about 500 feet. Usually coring is limited to an interval of about 40 feet, which includes the gray zone of the basal Moss Back sandstone and the upper few feet of the red Cutler sandstone. Radiometric logging costs 12 to 15 cents per foot. Costs were considerably higher during the period of major exploration than now. Assuming an average cost of \$3.50 per foot for drilling, including direct and indirect drilling costs, about \$7,700,000 has been spent for drilling in the area. The average discovery and development rate, based on production plus ore reserves, has been about 25 pounds U_3O_8 per foot of drilling, at a cost of about 14 cents per pound U_3O_8 developed.

Mining History and Costs

Vanadium ore production from the Chinle Formation at the Divide and Serviceberry mines in south Lisbon Valley was reported in 1917, 1940, and 1941. These same mines were reopened in 1948 (1) for their uranium content. Also in 1948, the Big Buck mines in the Cutler Formation in Big Indian Valley were mined for uranium. Intermittent production from these small deposits continued until 1952. In December 1952, Steen shipped the first ore from the Mi Vida mine (2, p. 3).

Production from the Moss Back sandstone beds has ranged from two to six million pounds of U_3O_8 per year and reached a peak production of over 6,377,000 pounds in Fiscal Year 1958, Table I. Due to the exhaustion of a few of the major ore deposits, the ore production rate started dropping in 1960 and has leveled off to about 4,000,000 pounds per year.

In the central and southern deposits, the vanadium content is high enough for that metal to be extracted economically. During the 1948–56 period, vanadium was extracted from ore that was shipped from these mines to some of the processing mills on the Colorado Plateau. However, most of the ore has been processed at the Atlas Corporation alkaline leach mill at Moab, Utah, and to date this mill has recovered only a small amount

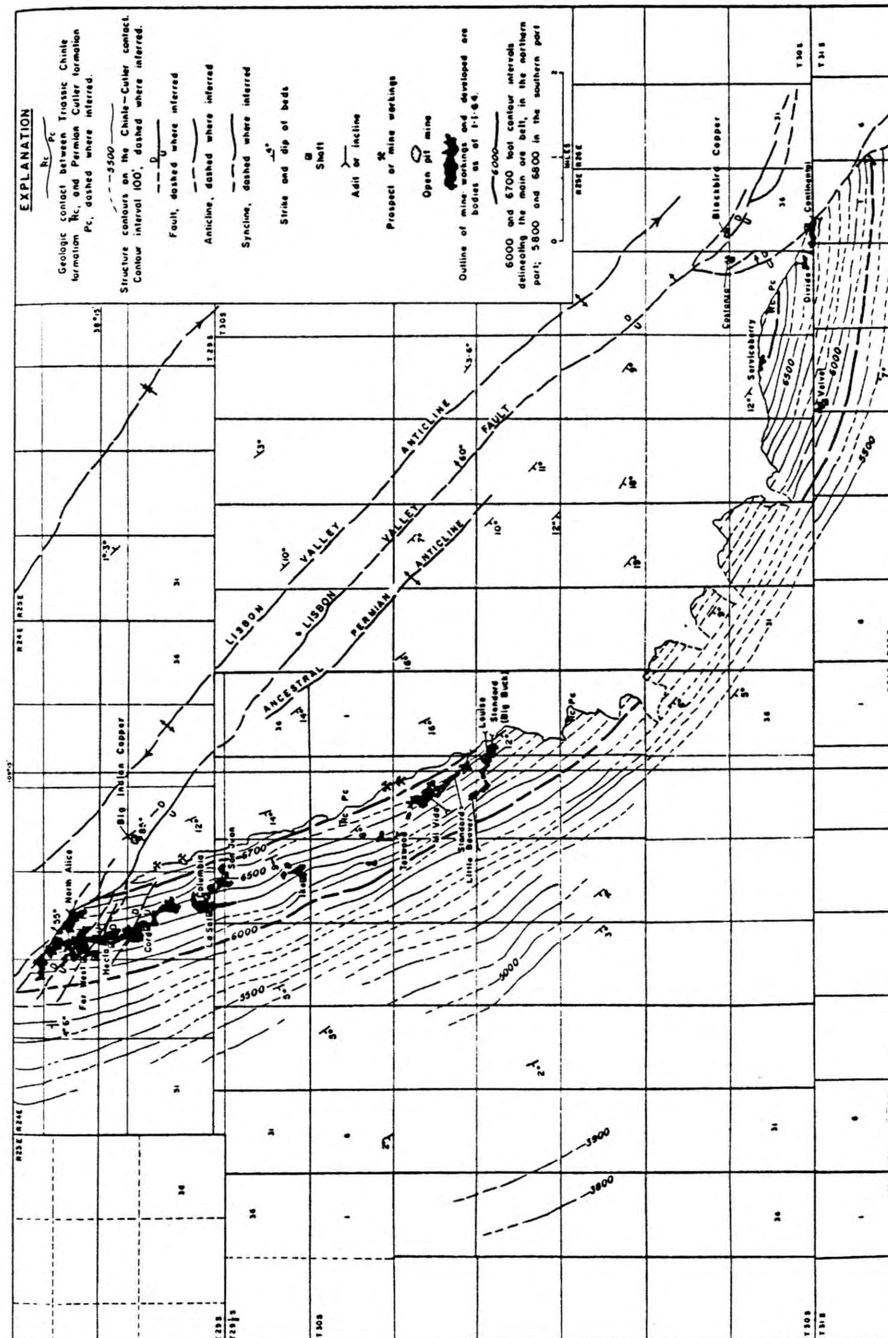


FIG. 2. *Structure Map of the Lisbon Valley Anticline, showing delineated Big Indian Ore Belt with ore bodies outlined.*

TABLE I. Annual Chinle—Cutler Ore Production 1948 through F. Y. 1965

	Tons	Pounds U_3O_8	Pounds V_2O_5*
1948 to July 1, 1953	15,288	143,093	361,862
F. Y. Ending			
July 1, 1954	71,391	742,452	1,749,724
July 1, 1955	208,781	1,998,764	3,271,362
July 1, 1956	394,713	2,795,701	2,643,571
July 1, 1957	592,304	4,707,193	3,409,168
July 1, 1958	773,042	6,377,746	2,401,720
July 1, 1959	771,229	6,349,628	3,821,721
Subtotal	(2,898,748)	(23,114,582)	(17,659,128)
July 1, 1960	760,585	5,649,143	Incomplete
July 1, 1961	640,536	4,179,223	vanadium
July 1, 1962	590,319	3,819,600	assay
July 1, 1963	418,477	4,309,452	records.
July 1, 1964	507,398	4,650,565	
July 1, 1965	330,748	2,806,691	
TOTAL	6,146,811	48,529,256	

* Note: The above production was compiled from U.S. Atomic Energy Commission ore receipts and includes ore shipments to numerous uranium processing mills on the Colorado Plateau. From November 1956, when the Moab mill went on stream, to 1960, the mill assayed the ore for vanadium, but after 1960 they discontinued the practice. Post-1959 vanadium assays are available on ore shipments to other plateau mills, but these shipments were sporadic

of vanadium on an experimental basis. Molybdenum assays ranging up to 0.25 per cent are common but very spotty in the Big Indian ores. Those deposits with anomalous molybdenum, such as the North Alice, South Almar, Mi Vida, Standard, and Velvet, normally assay only 0.03 to 0.07 per cent molybdenum.

Up to July 1, 1965, about 6,147,000 tons of ore at a grade of 0.39 per cent U_3O_8 containing about 48,530,000 pounds of U_3O_8, which is over 8 per cent of the U.S. total, had been mined from deposits in the Big Indian ore belt, including production from the Cutler Formation, Table I. Continuation of operations to 1971 should result in a total production of about 57 million pounds of uranium oxide worth about $450,000,000.

In the Big Indian belt, all underground mining methods allow full caving, and rarely is a stoped area accessible after the ore body has been depleted. The mining method selected was often determined by the adequacy of development drilling, by the knowledge of subsurface ground conditions, and by the kind of mining equipment the company had available. The mining equipment in use depends on the thickness of the ore and varies from jacklegs to jumbos for drilling; slushers and front-end-diesel-motor and air-motor loaders for mucking; battery or trolley motors with cars on track, Young-Shuttle Buggies, or Koehring's Dumpters for haulage.

Many of the major mines are accessible by shafts 400 to 800 feet deep, but the Mi Vida, Big Buck (Standard), Louise, and North Alice are entered by inclines or adits. Direct mining costs, plus haulage to mill of about 4.5 cents per ton mile, ranged from about $6.40 per ton for ore 15 to 45 feet thick, using the room and pillar method, to about $13.10 per ton for ore 3 to 8 feet thick, using the long-wall retreat method. The mines were dry, the ore bodies were fairly uniform in thickness, the dip of the bedded host rock was usually less than 10°, fracturing was not excessive, and the average grade was high for this type of bedded sandstone ore.

PHYSIOGRAPHY

Lisbon Valley is one of the many northwest-trending, subsequent stream valleys formed along breached salt anticlines in the Paradox Basin of the Colorado Plateau (20) (23) (28). The Cane Creek, Moab, Lisbon Valley, and Dolores (Slick Rock) anticlines are on the west edge of the deeper part of the basin; they all have Triassic and younger formations exposed; they all have uranium mineralization in basal Chinle sandstone beds.

The Lisbon Valley anticline is a compound structure formed by folding during both the Permian and Tertiary periods. The two anticlines have separate but nearly parallel axes; however, the younger Tertiary anticline forms the present physiographic structure. Weir, *et al.* (31) named the smaller, ancestral Permian anticline, the axis of which is west of the fault, the Lisbon Valley anticline, and the larger Tertiary anticline, the axis of which is east of the fault, the Lisbon Canyon anticline. The writer prefers to consider the smaller Permian anticline the ancestral Permian anticline and the larger Tertiary anticline the Lisbon Valley anticline (Figures 1 and 2).

The Lisbon Valley anticline covers an area about 21 miles long and 9 miles wide. Altitudes range from about 6000 to 7200 feet. Many high sandstone-capped cuestas, cut by canyons or gorges 200 to 500 feet deep, characterize this area, which is typical of the Colorado Plateau. Good access roads follow the valley floors. Except for a few drill roads, most of the hog-back ridges are inaccessible by motor vehicle.

GENERAL GEOLOGY

Igneous Rocks

No igneous rocks are exposed on the anticline, and none has been encountered in the numerous oil and gas test wells that have penetrated over 11,000 feet of sediments on the anticline. The nearest igneous intrusives are in the La Sal Mountains (South Mountain), 7 air miles north of the North Alice mine (Figure 1). During the Tertiary period, the diorite, monzonite, and syenite porphyrys of the La Sal laccoliths, dikes, sills, and plugs were intruded into and through at least 9000 feet of sediments (Pennsylvanian through Cretaceous in age) (15). No physiographic, structural, or mineralogic evidence appears to relate the La Sal igneous intrusives to the Lisbon Valley uranium deposits; however, some geologists postulate a relationship based on geographic considerations, on the Tertiary age of the major faulting, and on a few U^{238}/Pb^{206} isotope age determinations that indicate early Tertiary ages.

Stratigraphy

A generalized stratigraphic section at the anticline is shown in Figure 3, which symbolizes the lithology and gives approximate thicknesses of formations. Only the ore-bearing formations and those important in explaining the characteristics and the genesis of the Big Indian ore belt are described in the text.

CUTLER FORMATION The Cutler Formation at the Lisbon Valley anticline exemplifies the red bed facies (10, 11, 26) and ranges from 900 to 1800 feet in thickness. It thins gradually to the north and to the west and thickens to the east and northeast toward the Uncompahgre uplift. Throughout the salt anticline area, at the top of the Culter, there is a notable erosional unconformity. Erosional thinning of the Cutler over the anticlines indicates the Permian ancestry of most of the anticlines (24).

Where exposed in Big Indian Valley (Figure 1), the fluviatile upper part of the Cutler consists of alternating beds or lenses of light pink, orange, and buff mudstone, calcareous siltstone, and arkosic sandstone. The sandstone beds are well-sorted, are fine- to medium-grained, have a saccharoidal texture, and are as much as 50 feet thick. The sandstone is composed of quartz, feldspar, and biotite, with clay as the predominant binder, but locally calcite may be the main cement.

A few uranium ore pods in Cutler sandstone crop out along the west escarpment of Big Indian Valley about 100 feet stratigraphically below the Permian-Triassic nonconformity and 1000 to 1500 feet up dip and northeast of the eastern limit of the ore belt. Other ore pods are found in these massive sandstone units where they subcrop under the Moss Back ore deposits. Some ore pods are as much as 40 feet below the nonconformity, but most are within 6 feet of it. The Cutler sandstone beds, where exposed in the mine workings, appear to be more extensively bleached than they are on the rim outcrops. The thickness of this bleached zone below the unconformity does not appear to be directly related to the size or position of the overlying ore bodies but does appear to be related to the thicker and more porous of the Cutler sandstone beds.

MOENKOPI FORMATION The Moenkopi Formation, widespread throughout the Paradox Basin, does not crop out on the anticline (12) (27), but it is penetrated in oil and gas test wells drilled low on the flanks of the anticline (22). At the nearest outcrops on the Colorado River, the Moenkopi consists of interbedded dark-red to chocolate-brown, laminated, micaceous, ripple-marked shales and siltstones, containing a few thin, well-sorted, fine-grained sandstone beds. It is unconformably overlain by the Chinle Formation.

CHINLE FORMATION The Chinle Formation consists of fluviatile and lacustrine sediments and averages about 400 feet thick along the ore belt. The lower part is the Moss Back Member (type section in White Canyon), which ranges from 10 to 80 feet in thickness and was deposited on the Cutler erosion surface by streams flowing westerly and northwesterly. The upper part of the Chinle, which ranges from about 275 to 400 feet in thickness in this area, has not been precisely correlated, but it is probably equivalent to the Church Rock Member in White Canyon (11) (32).

The Moss Back Member, the uranium host rock in the Big Indian belt, is predominantly a fluviatile, cross-bedded, calcareous, fine- to coarse-grained, arkosic, poorly-sorted sandstone with interbedded lenses of mudstone and calcarenite conglomerates. Sparse to abundant coalified plant material, mostly as woody trash,

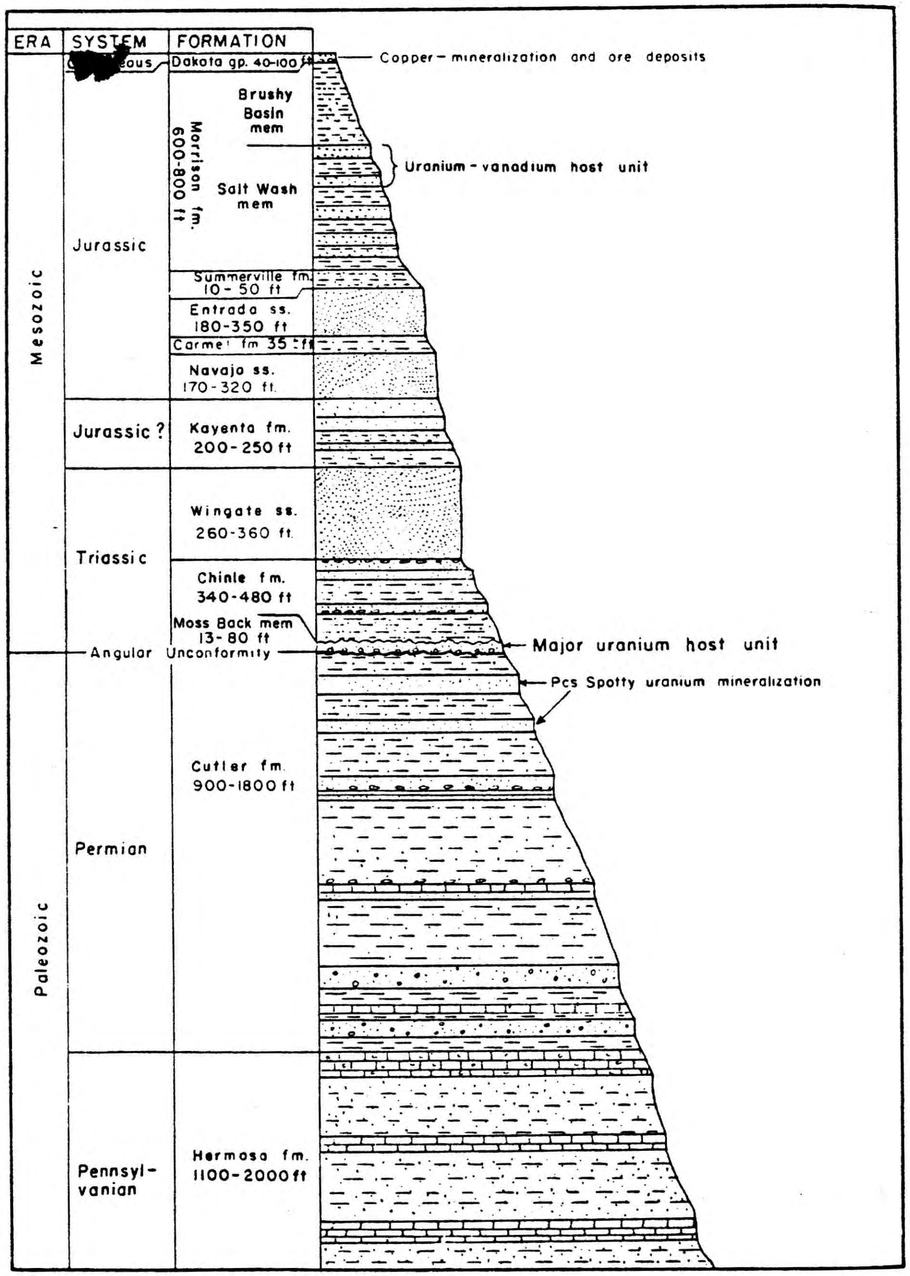


FIG. 3. *Generalized Stratigraphic Section in the Lisbon Valley Area.*

occurs in sandy lenses and pockets in and above the basal part of the ore sandstone or in highly coalified mudstone beds above the ore sandstone. The upper facies of the Moss Back Member contains proportionably more calcarenite conglomerate and micaceous mudstone beds. The Moss Back is gray-green to dark brown to greenish-gray and light gray in contrast to the variegated red color of the overlying upper Chinle beds. The Moss Back, in the northern and central part of the anticline, averages 45 feet thick, and in the southern part only 13 feet thick. The Moss Back grades lithologically upward into the variegated reddish-brown, purple, and lavender thin-bedded siltstones and claystones of the upper Chinle. Many of the claystones are lacustrine, and some of the clay beds are bentonitic, having been derived from volcanic ash (14) (38).

Isopach maps of the Chinle Formation indicate that this formation is over 100 feet thicker to the southwest and down dip from the central group of ore bodies than it is over these ore bodies, and, in contrast, it is about 100 feet thinner to the west or down dip from the northern group of ore bodies than it is over them. This notable thickening and thinning, 480 to 340 feet, is characteristic of fluviatile sediments in this region.

CUTLER-CHINLE NONCONFORMITY The angle of discordance between the beds of the Cutler and Chinle Formations at the northwest end of the ore belt is less than 2°; at the Standard-Big Buck mine near the central part of the ore belt, it is about 6°; and at the southeast end of the belt it is 3° to 4° (Figure 4). The paleotopography of the nonconformity varies from a fairly smooth, undulating surface with less than 5 feet of relief to a deeply scoured surface with over 30 feet of relief. The paleotopographic relief is greater in the area underlying the ore bodies in the central part of the ore trend where the greatest Permo-Triassic uplift and erosion occurred. Elongated scours or troughs are common, but no pattern or common orientation is evident. Distribution of the ore bodies is erratic with respect to the paleo lows and highs (Figure 5). Some large scours parallel the strike of the Cutler subcrops, and other scours trend down the dip of the Cutler beds, but there are no persistent or well-defined channels, such as the Shinarump (basal Chinle sandstone) channels of the White Canyon district (R. C. Malan, this volume). From general observation in the mines, it appears that the variable topography of the surface of nonconformity produced turbulent Moss Back streams and caused shifting of stream courses. This resulted in many facies changes and the deposition of intraformational conglomerates and thick sandstone lenses favorable for uranium emplacement.

Conspicuous bleaching, manifested by color changes of the rock from darker to lighter colors, has taken place in the upper Cutler and lower Chinle beds, predominantly along the nonconformity. The bleaching is noticeable throughout the Big Indian ore belt, occurring in, above, and below ore and extending laterally away from the ore deposits, although it is less conspicuous in areas remote from known ore. The greater intensity of bleaching indicates that strong reducing conditions, caused either by migrating humic acids derived from diagenetic processes, by sulfur-bearing waters rising from salt anticlines or oil fields, or by uranium mineralizing solutions, existed in and near the ore.

In the vicinity of ore deposits, the contact between the Cutler and Chinle beds is often difficult to identify, particularly where the basal Chinle sandstone contains an abundance of reworked Cutler arkosic sands or where the beds on both sides of the contact are bleached to light gray, are calcareous, are uraniferous, and are otherwise lithologically similar. The following mineralogic, lithologic, and color variances may be used to locate the contact. The Moss Back has an abundance of carbon specks or woody fragments, an abundance of red or gray subangular chert pebbles and concretions, and some muscovite and chlorite. It is poorly sorted and is more cross-bedded and more coarse-grained than the Cutler. The Moss Back in the vicinity of ore is light to dark-gray, greenish-gray, or buff with some limonite specks. The Cutler sandstone, on the other hand, has an abundance of fresh and altered feldspar and of biotite altered to chlorite and has a few thin gray and red chert beds or lenses. It is normally friable and fairly well sorted. Where overlain by ore, it is mottled-gray, tan, brown, and pink. The mottled coloration grades downward into a normal rusty-red or brown (12) (18).

Structure of the Anticline and Fault Zone

The Lisbon Valley anticline is a faulted asymmetric anticline, formed by flowage of salt and gypsum in the Paradox Member of the Hermosa Formation (Figures 1, 2, 3, 4). Over 6000 feet of salt and anhydrite beds have been penetrated in a few of the oil and gas test wells. According to Budd (22, p. 121),

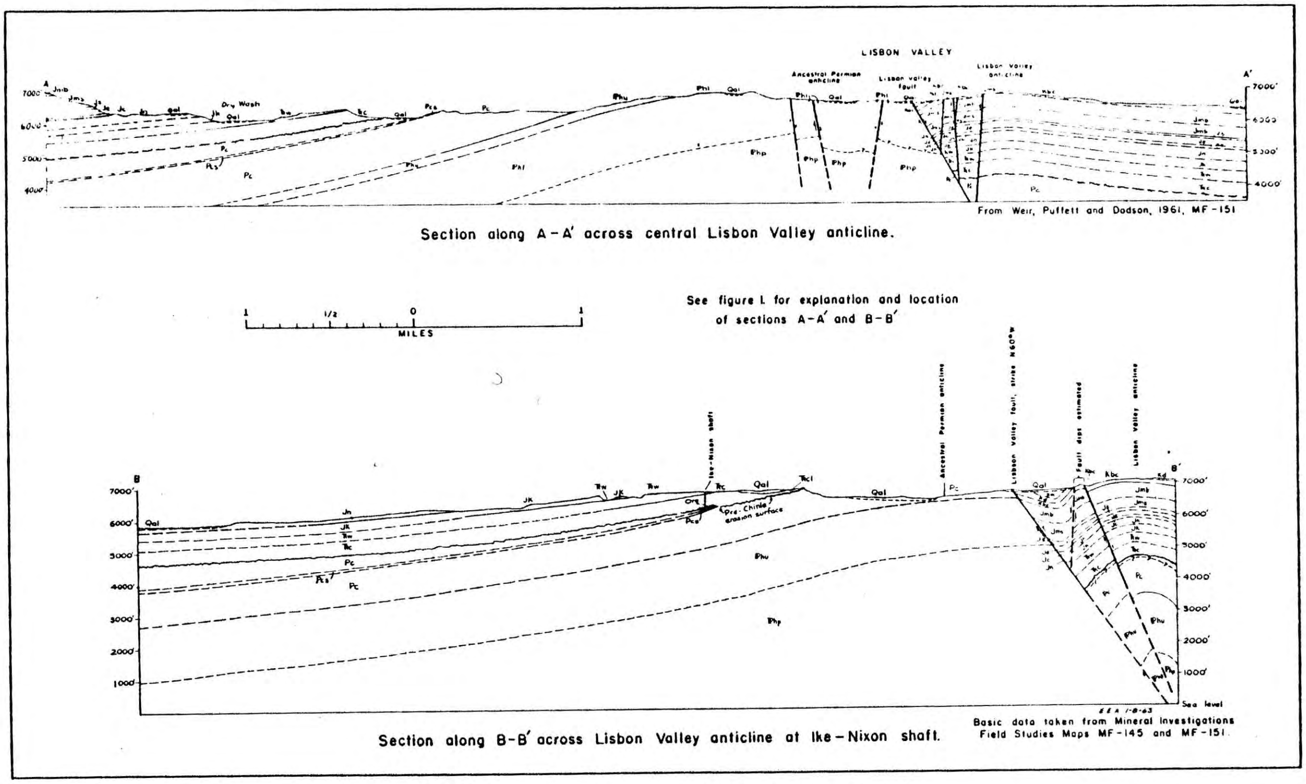


FIG. 4. *Geologic Sections across the Lisbon Valley Anticline.*

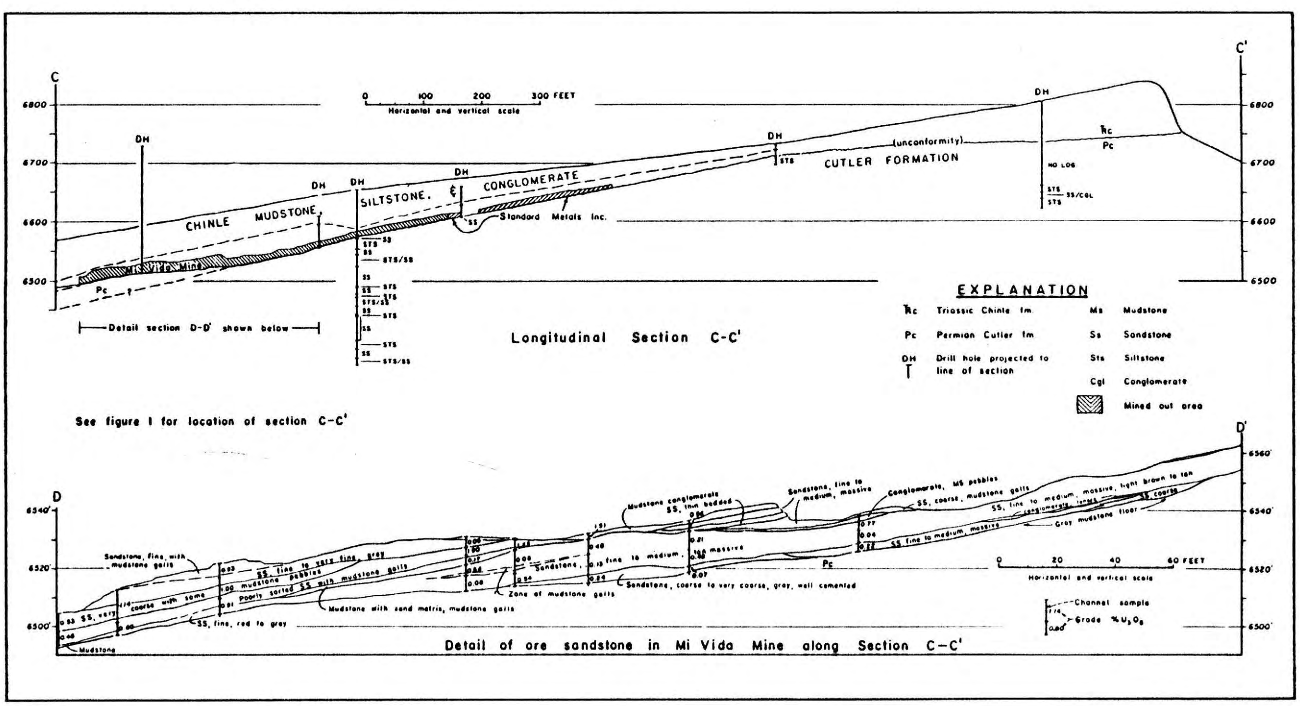


FIG. 5. *Geologic Section across the Ore Body at the Utex (Mi Vida) and Standard (Big Buck) Mines.*

the anticline has 3000 feet of vertical closure at the surface.

The anticline is faulted along its longitudinal axis by the Lisbon Valley normal fault. The fault plane has dips ranging from 50° to 85°NE. The surface trace of the fault is about 21 miles long but probably has a greater length at depth. The fault zone contains gouge, shear bands, and closely spaced step faults with a variety of dips, some reversed. Adjacent beds are often broken by drag and gash fracturing. At the crest of the anticline, the displacement is about 4000 feet, and Hermosa beds butt against Dakota beds; 8 miles northwest at the North Alice mine, the displacement is about 2000 feet, and Chinle beds butt against Morrison beds. Displacement decreases toward the northwestern and southeastern ends of the anticline, where the fault splits into a number of smaller hinge-type branches. These branching faults have different dips and strikes, which complicate interpretation of the structural geology. Horst and graben blocks are common along the fault but are most prevalent at each end of the anticline.

Almost all branch faults and major fractures are parallel or subparallel to the Lisbon Valley fault and the long axis of the anticline. At the Cord, Far West, and North Alice mines, subsidiary normal faults dip to the northeast and southwest and displace the ore bodies (18). Small strike slip displacements are measurable where the faults are exposed underground (Figure 2). The intensity of fracturing or the strike of the fractures does not appear to control the location or shape of any observed ore body. However, the longitudinal fractures, which are usually open, have caused mining problems and unexpected caving.

On the southwest flank, the Chinle beds dip 10° to 15°SW, and the Cutler beds dip as much as 20°. On the northeast flank, the Jurassic and Cretaceous beds dip 5° or less to the northeast. All bedding dips decrease toward the ends of the anticline (Figures 1, 4).

The difference in the shape of the Permian anticline from the shape of the Tertiary anticline is indicated by: (1) the approximate 15° angle between the strike of the Cutler beds and the strike of the Chinle beds in the northern part of the ore belt; (2) by the flattening of the dip in the Cutler beds on the crest of the ancestral Permian anticline; and (3) by the difference in the discordant angle of dip between the Chinle and Cutler beds throughout the anticline. The present location of the ancestral Permian anticline, now a minor anticline or flexure on the southwest flank of the Tertiary anticline, is shown on Figures 1, 2, 4.

Geologic History of the Anticline

In Pennsylvanian time, a deep basin developed southwest of the northwest-trending Uncompahgre Highland. A thick sequence of marine shale, limestone, and evaporites accumulated in this basin; the Lisbon Valley area is on the southwestern edge of the deeper part of this basin. Plastic flow of the evaporites into northwest-trending zones of weakness, folds or grabens, caused by fracturing and faulting, initiated the formation of the salt anticlines of the region (24,35).

Uplift of the ancestral anticline started in Late Permian time and probably continued into Late Triassic time. During this period, a local topographically high area developed that was exposed to extensive erosion. Hundreds of feet of Cutler and Moenkopi sediments were denuded from the crest of the ancestral arch, prior to deposition of fluviatile sediments over the structure by westward and northwestward flowing Moss Back streams. Mild uplift probably continued during deposition of the Moss Back sediments, as is evidenced by the occurrence of intraformational conglomerates that contain mudstone, calcarenite, and chert pebbles or fragments derived from erosion of Permian and Triassic sediments.

Emplacement of uranium minerals to form the Big Indian ore belt started soon after deposition of Chinle sediments and probably continued until movement of connate waters, caused by compaction of sediments or by regional folding, became negligible. During the ensuing Triassic, Jurassic, and Cretaceous periods, the Paradox Basin continued to subside and thousands of feet of eolian sandstone, fluviatile sandstone and mudstone, marginal marine, marine, lake sediments, and volcanic ash beds were deposited over the region. This depositional sequence was interrupted by brief hiatuses, which probably coincided with some regional uplifting. Proof of continuous or intermittent salt flowage during this period is not available, but it is inferred, from the variations in formation thicknesses and from the hiatuses in the overlying sediments, that mild salt flowage could have occurred intermittently (19,24,27).

Major uplift of the present Lisbon Valley anticline, which was superinduced on the ancestral Permian anticline, and the major offset along the Lisbon Valley fault occurred during the Laramide orogeny. Salt and gypsum flowed into the footwall of the fault, thrusting the footwall block upward and southwestward. Tilting of the southwest flank accentuated the arcuate bend of the ore belt. In the hanging wall, away from the fault zone, the beds were elevated only slightly. Rejuvenated flowage of evaporites and accompanying movement along the fault probably continued into Oligocene or Miocene time and still may be active. The unoxidized and unaltered condition of the brecciated fault zones along some of the small subsidiary faults, which displace uranium ore bodies at the north end of the belt, indicates that some of this faulting may be fairly recent.

Extensive erosion of the Lisbon Valley anticline started in Late Eocene time (35), removed approximately 5000 feet of sediments, and exposed Pennsylvanian sediments on the crest of the anticline.

ECONOMIC GEOLOGY

Size, Shape, Grade, and Distribution of the Uranium Deposits

The 15-mile-long by half-mile wide Big Indian ore belt consists of numerous intermittent bodies ranging in size from 500 to 1,500,000 tons of ore. A five-mile stretch of the south-central part of the ore belt has been removed by erosion, leaving about 6 miles of coalesced or separate ore deposits in the northern part of the belt and about 4 miles of scattered smaller deposits in the southern quarter. Possible evidence that ore bodies have been eroded, between the Standard and Serviceberry mines, is indicated by the anomalous radioactivity in the alluvium of Big Indian Valley in the vicinity of Big Indian Rock (7), and by the existence of uranium mineralization on a point of Moss Back cropping out in section 30, T30S, R25E.

The ore belt contains two large groups of nearly coalesced deposits from which 74 per cent of the districts ore has come as of July 1, 1965. Approximately 20,000,000 pounds of U_3O_8 has been mined from the north group of deposits and 16,000,000 pounds from the central group. Three intermediate-size ore deposits lie between the two larger groups and production from them ranges from 2,800,000 to 3,500,000 pounds of U_3O_8. Eight smaller ore bodies, ranging in size from 500 to 90,000 tons or ore, are scattered throughout the ore belt (Figure 2). In general, the ore deposits range from a few inches to 45 feet in thickness, with an average thickness of 6 feet. The ore has an average grade of 0.39 per cent U_3O_8, contains about 15 per cent $CaCO_3$, and has a dry bulk density factor of about 13 cubic feet per ton. The northern 6 miles of the big Indian ore belt contains about 2600 acres, of which about 300 acres is underlain by ore. All the deposits are irregular, amoeba-shaped masses that lie concordantly to the bedding. Within each deposit, there is a notable variability in thickness and grade, but in general, the grade of uranium ore drops sharply at the edges of the ore bodies. This sharp cutoff precludes the probable existence of any large reserves of low-grade uranium ore.

Mineralogy and Geochemistry of the Big Indian Ore

Uraninite, $UO_2 \cdot UO_3$, is the principal uranium ore mineral. Intimately associated are small amounts of coffinite, $U(SiO_4)_{1-x}(OH)_{4-x}$, and the vanadium minerals montroseite, $VO(OH)$, doloresite, $V_2O_4 \cdot nH_2O$, and vanadium clay or vanadium hydromica. Secondary uranium and vanadium minerals, such as metatyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}7H_2O$, pascoite, $Ca_3V_{10}O_{28} \cdot 16H_2O$, and corvusite, $V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$ are found in areas of oxidation, but they are of no quantitative importance (8). Beautiful high-grade uraninite ore specimens, usually replacements of coalified wood, have been collected from many of the mines; some samples assay about 80 per cent U_3O_8. Ore minerals dominantly fill the interstices between grains of sand, but they also replace calcite, carbonaceous plant remains, and, to a lesser extent, detrital quartz and feldspar grains and other accessory minerals.

The principal detrital constituents of the quartzose sandstone host rock are quartz, limy rock fragments (calcarenites), feldspar, mica, chert, clay, and coalified plant remains. Minerals commonly associated in anomalous quantities with the ore deposits are barite, celestite, galena, pyrite, chalcopyrite, chalcocite, molybdenite, chalcedony, greenockite, and sericite (8) (31).

Paragenetic studies (8) indicate that detrital minerals were deposited and cemented by calcite; silica and barium sulfate solutions precipitated authigenic silcia and barite; local deformation of the mudstones and some of the less competent sandstone beds resulted in fracturing of quartz, feldspar, and calcite; and ore solutions penetrated the sandstone, replaced some minerals and plant remains, and precipitated in the voids. In places, there was also fracturing of the detrital grains after uraninite was formed, but before introduction of some of the galena and greenockite. Calcite was probably deposited, dissolved, and redeposited many times; consequently, calcite is replaced by uraninite and other minerals and in turn replaces them (13, p. 548).

Geochemical and mineralogic studies (17, 31) show that: (1) lead correlates with uranium, (2) molybdenum occurs as a halo above some of the central and southern ore bodies, (3) vanadium ranges from one-third to three times the per cent of uranium in the Mi Vida mine and in other deposits to the south, and (4) is negligible in the Ike-Nixon mine and in other deposits to the north. Most of the ore from the Mi Vida mine on the south may be classified as uranium-vanadium or vanadiferous uranium ore because the ore will usually assay over 0.40 per cent V_2O_5. Other extrinsic elements, anomalous in or around the ore bodies, are arsenic, barium, cadmium, copper, iron, strontium, and zirconium and sometimes selenium, cobalt, zinc, yttrium, and columbium.

Mill heads average about 15 per cent $CaCO_3$, but the $CaCO_3$ content differs considerably from deposit to deposit within the ore belt and also from place to place in the individual ore bodies. The calcium carbonate concentration is highest where it occurs as a cement and as detrital grains. Rarely does high-grade ore assay over 20 per cent $CaCO_3$. Commonly the $CaCO_3$ has been recrystallized to form visible sand crystals showing a poikilitic texture (8). Although these deposits are hundreds of feet above the present water table, the low permeability, due to cementation by calcite, has protected them from oxidation and leaching by vadose waters.

Coalified wood fragments are common, but show little spatial relation or quantitative correlation to the ore deposits. Coaly material is usually in the clayey beds immediately above the ore-bearing sandstone, where it is concentrated along bedding planes and is disseminated in mudstone conglomerates. Because the coaly layer is usually barren and is embedded in mudstone, it is not broken into during mining, which may account for the low carbon content of the mill heads. Within the ore bed, some coalified logs are partially replaced by uraninite, but others are not.

Isotope Analyses and Geochronology of the Big Indian Ore

Uraninite ore samples collected from the North Alice and South Almar (Cord) mines (Figure 1) by the author were submitted to John Rosholt (U.S.G.S.) for isotope analysis. The results of isotope fractionation studies on U^{238}, U^{235}, and U^{234}, as given in J. N. Rosholt's letter on May 13, 1964, for these samples, are summarized in this quotation: "The Lisbon Valley samples studied show extremely good examples of radioactive equilibrium between U^{238} and U^{234}. No other area in sandstone-type ore deposits, yet analyzed, has indicated such an environment of consistently stable uranium mineralization. The deviation from the equilibrium U^{234}/U^{238} ratio is within ± 1 per cent for all six samples, thus within our experimental error. There is no evidence to indicate that the uranium mineralization in the fault zone (at the mines mentioned above) occurred at a more recent time than that some distance from the fault zone."

Uranium-lead isotope age determinations range from 85 to 295 m.y. and disagreements on interpretation and value of the age determinations are acknowledged by many (16, 34,36). Most of the U^{235}/Pb^{207} apparent age determinations range between 150 and 210 m.y. and imply that the ore deposits are Jurassic to Triassic in age.

Favorable Lithology of the Host Rock

Lithologically the most favorable host rock is a gray, poorly-sorted, fine- to coarse-grained, calcareous, arkosic quartzose sandstone containing some interbedded mudstone and limestone pebble conglomerates and some mudstone and siltstone lenses, all poorly sorted and of variable permeability. The highest-grade ore is in semi-permeable, fine-grained, sandy lenses that contain less than 30 per cent calcium carbonate as cement or as clastic limestone grains. Jasper, smoky quartz, pyrite, and a reddish-brown or pink calcite, colored by hematitic inclusions, are common in the higher-grade deposits. There is an abundance of mudstone pebbles and coalified wood-trash either in or directly overlying the host rock.

Stratigraphic Position of the Ore Bodies

The Chinle Formation thickens and thins notably, 480 to 340 feet in short distances. There is no apparent relation of the thickness of the Chinle Formation or of the Moss Back Member to the position of the ore belt.

Usually, within the ore belt, the larger ore deposits are where the Moss Back Member is thicker, such as across the north-central part of the anticline, but the higher-grade deposits in the northern ore bodies are in thin basal

sandstone units. Although thinner and lithologically less favorable Moss Back sandstone is spread over the southern part of the anticline, even this less favorable host rock, within the ore belt, contains numerous small but minable ore deposits. Persistent paleostream channels, which were scoured into the Cutler paleotopography and later filled with thick lenses of favorable Moss Back sandstone, do not occur under the Big Indian ore belt. Elongated sandstone-filled scours, containing uranium ore, do occur at some of the larger ore deposits, but their control of any ore distribution is local.

Prevalently the lowest sandstone or conglomerate unit of the Moss Back Member is the uranium host rock, and it rests on or within a few feet of the Cutler-Chinle nonconformity. Within a host unit, the lithology and the sedimentary structural features, which directed the course of the ore fluids, control the localization of the ore. The ore bodies may cut across bedding planes within the host and may occur above and below a mudstone seam, but they do not cross through intercalated mudstone beds.

Lekas and Dahl (12) in 1956 and Puffett and Weir (21) in 1959 recognized the spatial relation of the Moss Back ore deposits to the subcrop, at the nonconformity, of a Cutler sandstone unit, called locally the "sugar sand." Where this unit crops out at the Standard mine portal, it is a 30-foot-thick, friable, porous, saccharoidal, fine-grained, light-gray sandstone. Underground it can be traced from the portal, in a northwesterly direction, to the north end of the Mi Vida mine. This "sugar sand" has not been definitely traced north of the Mi Vida mine. It is believed that the northern ore bodies are underlain by different, stratigraphically lower, but physically similar Cutler sandstone units. The common occurrence of this sandstone unit or its physical equivalent under the ore belt has been a useful guide in exploration. Lekas and Dahl suggest that the subcrop of this porous Cutler sandstone unit acted as a conduit for ore solutions, thus localizing the ore deposits within the delineated belt, and Noble (37) suggests that a pressure change occurred at the intersection of the two (Cutler and Chinle) acquifers. It is suggested by the writer that the Cutler porous sandstone units may have acted as a conduit for rising gases or solutions that precipitated the uranium minerals or changed the pH or Eh sufficiently to permit precipitation.

It has been suggested by some geologists (6,12) that the position of the erosional pinch-out of the Moenkopi Formation, around the southwest flank of Lisbon Valley anticline, was influential in positioning the ore belt. They theorized that it acted as an impervious cap to rising uraniferous solutions, until the pinch-out was reached or that the uraniferous solutions, migrating laterally in the fairly permeable Moss Back beds, were confined between the quite impermeable Moenkopi and upper Chinle beds. The validity of this hypothesis depends on the location of the Moenkopi pinch-out, which has not been determined.

Structural Position of the Ore Bodies

A structure map, (Figure 2), showing contours drawn on the nonconformity at the base of the Chinle Formation, shows that the 6-mile-long northern half of the ore belt lies between the 6000- and 6700-foot contours and the southern one-quarter of the ore belt is between the 5800- and 6800-foot contours. Furthermore, over 90 per cent of the ore occurs between the 6200- and 6700-foot contours in the northern half of the ore belt. Exploration drilling to date has failed to discover large ore bodies on the southwest flank of the anticline outside of this delineated belt. This vertical limitation was first referred to in 1955 as the "magic contour interval"(6).

The horizontal width of the ore bodies or ore body aggregates along the trend of the ore belt ranges from 800 to 3000 feet in the northern section. At the northwest and southeast ends, where the ore belt is intersected by the Lisbon Valley fault, the ore bodies are spread over a wider area, 3000 feet to over 3600 feet across the trend, giving the appearance that the ore is spread out along the Lisbon Valley fault. This spread of the ore belt may be explained by a flattening of the angle of nonconformity between the Cutler and Chinle beds from 6° at the crest to 3° at the ends, and by a gentle flattening of the dip of these beds at each end of the anticline.

The limitation of the ore belt within the "magic contour interval" may imply a water table or a water-oil-gas interface as a control for positioning the Big Indian uranium deposits (30). Another interpretation is that the structural position of the ore belt may represent an ancestral water table where the descending vadose water encountered connate water.

Summary of Geologic Characteristics of the Big Indian Ore Belt

(1) Most of the ore in the 15-mile-long by half-mile wide Big Indian ore belt is within a 500-foot elevation interval.

(2) The large ore bodies are hundreds of feet above the present water table, but more than 95 per cent of the ore is unoxidized uraninite.

(3) The spread of the ore bodies across the belt is appreciably wider at the northwest and southeast ends of the anticline, where the beds have a more gentle dip and the Cutler-Chinle angle of nonconformity is less than it is along the central part of the southwest flank.

(4) The bedded ore deposits are displaced, by Tertiary normal faulting, at the North Alice, Far West, Cord, and Continental (Section 36) mines.

(5) The main ore deposits are usually confined to the lowest sandstone bed in the Moss Back Member of the Chinle Formation.

(6) Uranium deposits appear to be more persistent or to occur more often where porous, friable, fine-grained Cutler sandstone units, bleached to light gray, subcrop at the nonconformity under lithologically favorable Moss Back sandstone.

(7) Small deposits of uraninite ore are in the Cutler sandstone adjacent to the Moss Back ore deposits. Carnotite deposits also occur about 500 feet laterally up-dip and at approximately the same elevation, but lower stratigraphically, in the Cutler section than the ore occurrence subjacent to the Moss Back ore.

(8) Persistent bleaching, resulting from the leaching of ferric oxide, is unmistakable in the Chinle and Cutler Formations in and around uranium ore and particularly along the nonconformity.

(9) Abundant coalified plant material occurs as lenses or as aggregations in and above the basal ore sandstone or as carbon trash disseminated in carbonaceous mudstone beds above the ore sandstone.

(10) Zoning of vanadium within the ore belt is manifested by the notable increase of the V:U ratio in the Mi Vida and other ore bodies to the south and by some differences, although erratic, in the up dip and down dip vanadium to uranium ratio within the ore bodies.

(11) Anomalous copper is spotty in Moss Back uranium deposits and in nearby barren Moss Back sandstone. In contrast, copper ore containing only traces of uranium, is common in the Dakota Group sandstones at many places along the Lisbon Valley fault.

(12) Molybdenum occurs as an anomalous halo around some of the southern ore bodies and is anomalous in samples collected from ore deposits adjacent to the subsidiary faults in the northern part of the ore belt.

(13) No anomalous radioactivity has been found along the trace of the Lisbon Valley fault or along the fault zone at depth, except where the Moss Back, containing uranium mineralization, butts against the fault, and ore bodies do not appear to have been localized or shaped by fractures.

Ore Genesis and Mode of Deposition

Except for slight variations in their theory, Steen (2), Isachsen (6), Loring (18), Weir and Puffett (29), and Jacobs and Kerr (39), postulate a hydrothermal origin, advocating access of rising uranium, vanadium, and copper solutions by way of the Lisbon Valley fault or by way of some unnamed conduit. Lekas and Dahl (12) discuss a variety of hypotheses of origin and localizing features. Kennedy (25,31), and Noble (37), each postulate, but in a slightly different manner, that connate waters, which were expelled from fluviatile sediments during compaction, may have been the ore-forming and ore-transporting fluid. Waters and Granger (3) and Schultz (14, 38), discuss how the extrinsic elements may have been derived from Chinle volcanic ash or tuff beds.

The possibility that uranium and other extrinsic elements in the deposits could have been precipitated by reduction from telethermal, connate, or meteoric waters leaves the genesis open to many hypotheses. The hypothesis that the ore solutions rose through the thick series of Pennsylvanian gypsum, halite, shale and limestone beds, and then used the Cutler porous sandstone beds as conduits to known points of deposition, seems improbable. Also, the absence of supporting evidence of hydrothermal activity and the absence of any ore deposits localized along fractures or faults that could have acted as conduits for ascending thermal solutions makes it improbable that these deposits are of hydrothermal-hypogene origin.

In general, the geologic features of these deposits appear to be congruous with the theories postulated by Kennedy, Noble, and the writer, and with some of the theories suggested by Lekas and Dahl.

The writer believes that the uranium was indigenous to the Chinle Formation; was mobilized or released from the siliceous glass by diagenetic processes, which started soon after deposition of sediments; was moved laterally or outward from the least permeable sediments into more permeable sandstones, as consolidation and compaction continued; and was probably comingled with vadose ground waters. Under hydrostatic forces or water of compaction forces (30,37), the solutions moved laterally through the permeable Moss Back sandstone toward points of expulsion or precipitation. At times, movement may have been rejuvenated by ground water flushing the aquifer.

It is reasonable to assume that the uraniferous solutions contained some natural gases, such as methane and dense carbon dioxide; that they were mixed with ground waters; that the uranium was transported as a nearly neutral, highly stable, uranyl dicarbonate or tricarbonate complex; and that precipitation resulted from reduction of hexavalent uranium to form uraninite (33). As explained by Garrels (5), the part played by liquid or gaseous CO_2 in the dissolution and transportation of uranium is not fully understood, but, because large quantities of CO_2 are associated with the Mississippian oil reservoir under the northwest flank of the Lisbon Valley anticline, this probable relationship should be considered and studied. Upon reaching a favorable depositional site, precipitation may have been caused by change in the pH and Eh, or by reduction in pressure, or by encountering hydrogen sulfide produced by bacterial action on carbonaceous material (34). The presence of an abundance of coalified plant material within the host rock and the probable leakage into the Cutler-Chinle nonconformity of natural gas or sulfur-solutions from the Mississippian oil and gas reservoirs beneath the ore belt, assures the existence of sufficient reducing agents (16).

The mechanism suggested, if effective, implies that these deposits were emplaced during the fairly static period following deposition of the fluviatile Chinle Formation; that emplacement continued during burial under thousands of feet of Triassic and Jurassic sediments; but that emplacement ended prior to the start of the Laramide orogeny. The ore deposits were positioned within the ore belt by either a water-gas interface (30) or by a connate-vadose water interface near the crest of the ancestral Permian anticline, or by subcrops of either the porous upper Cutler sandstones or the Moenkopi Formation at the nonconformity around the flanks of the ancestral anticline. The multiple oxidation-solution-migration-accretion theory of Gruner (9), does not explain some of the geologic conditions described above, but it explains enough of these conditions to make this theory worthy of consideration.

Ore Guides and Potential of the Area

Future exploration along the Big Indian ore belt may be guided by the stratigraphic and structural ideas and favorable host rock characteristics described herein and by giving due consideration to the probable shape and size of the target. Favorable Moss Back beds are spread over the northern part of the Permian anticline, with the thickest sandstone beds on the crest of the anticline. Less favorable sandstone beds cover the southern part of the anticline.

The more irregular the relief of the Cutler paleotopography, the better are the chances of finding lithologically favorable Moss Back sandstones. The scours trending parallel to the strike of Cutler beds are deeper and commonly contain uranium deposits on the up dip side of the scour.

The favorable characteristics of the Moss Back on the northeast side of the Lisbon Valley fault have not been thoroughly evaluated. A Moss Back thickness of about 33 feet has been interpreted from a gamma log of a deep hole drilled northeast of the fault. Geologic logs of other deep test wells drilled northeast of the fault, and still on the structure, indicate a variable thickness of Moss Back sandstone and probably the occurrence of Moenkopi sandstone under the Moss Back. Unless more rapid changes exist in the character of the Chinle streams than has been observed, it appears logical to assume that favorable Moss Back sandstone beds do exist across the Lisbon Valley fault.

In summary, it is believed that the original ore belt encircled the crest of the Permian anticline as a band. The southwest flank of the anticline has been thoroughly explored for large deposits. An extension of the Big Indian ore belt, similar in size and grade to the known ore belt, probably occurs in the downthrown block northeast of the Lisbon Valley fault at depths of 2400 to 2700 feet beneath the Dakota-capped surface. As of the fall of 1965, only nine holes had been drilled into the Moss Back sandstone northeast of the fault, which leaves this area as the most favorable unexplored area remaining on the Lisbon Valley anticline.

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