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GEOLOGY OF LUKACHUKAI MOUNTAINS AREA,
APACHE COUNTY, ARIZONA

by

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with a section on SURVEY CONTROL

by

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(Grand Junction, Colorado)
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# GEOLOGY OF LUKACHUKAI MOUNTAINS AREA, APACHE COUNTY, ARIZONA

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ABSTRACT

Thirteen thousand feet of sedimentary rock were deposited in the Lukachukai Mountains area prior to Laramide deformation at the end of Cretaceous when the major structural features were formed. Monoclinal flexures may have resulted from draping of the surficial sediments over normal or reverse faults at depth. Erosion during early Tertiary stripped almost 9,000 feet of rock from the Lukachukai Mountains before deposition of the Tohatchi and Chuska formations in middle Tertiary. Intrusion of minette and diorite porphyry, differentiated from a large subsurface magma, took place during Pliocene. Hydrothermal solutions from the magma ascended zones of fracturing or faulting below the monoclines and around the Carrizo laccolith. Ground water in the Salt Wash sandstones was impregnated with solutions containing uranium. The water moved freely through thick, continuous sandstones, but was trapped by decreasing thickness and permeability. The decreased transmissibility of the sandstone caused "stagnation" of the ground water and precipitation of uranium minerals. No geologic changes have taken place since Pliocene to alter on a sizable scale the location or orientation of ore bodies.

A structure contour map of the Lukachukai mesas shows that ore is not localized by structural control. Subsurface maps of ore sandstones on Mesas IV½ and V indicate that ore is restricted primarily to the central and median parts of sandstone lenses and is adjacent to lateral changes in color from ore-bearing tan or gray sandstone to barren red sandstone. The maps can be used to guide drilling and to re-evaluate areas which have been drilled, both in the Lukachukai district and elsewhere.

Examination of surface stratigraphy is useful for determining areas favorable for ore. Detailed information from rim exposures about sandstone thicknesses, color changes, and other ore criteria can be added to the subsurface maps.

INTRODUCTION

Purpose and Scope

The purpose of this paper is to present the geologic facts which have been discovered thus far about the Lukachukai area and to draw conclusions about uranium mineralization. Basic data of general nature are included to facilitate the work of future geologists in this area who may find the information applicable to new ideas.
The author was assigned to the Lukachukai Mountains for seven months (July 1951 to February 1952). During that time, several aspects of the geology of the Lukachukai Mountains were studied in detail, namely: tectonic structure, Salt Wash stratigraphy, distribution of uranium mineralization, localization of uranium ore bodies, and criteria for the recognition of favorable ground. These particular problems, in addition to the regional geology, were studied in a more general manner over the region of northeast Arizona and northwest New Mexico. The study was conducted by examination of the literature, discussions with other geologists, and several reconnaissance trips.

Acknowledgments

The writer is indebted in particular to Leo J. Miller who participated in the work from July 1951 to September 1951, and to Richard D. Blum who participated in the work from September 1951 to February 1952. Their intelligent and untiring efforts were essential to the completion of this project. E. V. Reinhardt suggested many of the problems which were studied and he field-checked the stratigraphic geology. At all times, members of the Exploration Section attached to Lukachukai Project No. 2 were helpful and cooperative. M. E. Crew, J. David Lowell, Lewis Roberts, and A. N. Yater logged all of the subsurface data and assisted in the interpretation of that data. In addition, many other members of both the AEC and USGS have contributed to this paper by advice and published material.

Geography

The Lukachukai Mountains are located on the Navajo Indian Reservation in Apache County, northeastern Arizona, about 30 miles south and 12 miles west of the Four Corners (Index Map, fig. 1). Cove, Arizona, at the foot of the mountains, is the base for AEC operations in this area and may be reached from a point on U. S. Highway 666 five miles south of Shiprock, New Mexico, by 35 miles of graded road. An airstrip, suitable for light planes, is located 3 miles east of Cove.

The Lukachukai Mountains are the northwest end of the Chuska Mountains which are an erosion remnant of Tertiary sandstone lying unconformably on truncated Mesozoic rocks. Intrusions and extrusions of basic igneous rock are scattered over the Lukachukai and Chuska Mountains. The main ridge of the Lukachukai Mountains maintains an elevation of 8,800 feet above sea level; isolated peaks rise several hundred feet higher and one peak attains an elevation of 9,400 feet. The valley floor at Cove is about 6,500 feet in elevation. Fingerlike erosion remnants, called "mesas" in all the Lukachukai reports, project from the mountains on the northeast, northwest, and southwest rims.
Previous Work

The first geologic work in this region was done by Emery (1916) and Gregory (1917), the work of the former being confined to the Carrizo Mountains, whereas Gregory made a reconnaissance study of the entire "Navajo Country." Williams (1936) studied the igneous rocks in this same region. Jurassic stratigraphy in the Four Corners region has been studied and disputed by a series of writers: Baker, Dane, and Reeside (1936; 1947), Goldman and Spencer (1941), Stokes (1944), and Wright and Becker (1951). A detailed study of the Morrison was published by Craig, et al (1951). Careful studies of Salt Wash stratigraphy and uranium-vanadium occurrences were made in the Carrizo Mountains area immediately north of the Lukachukai Mountains by Union Mines Development Corporation (Weber, 1947). Stokes (1951) studied the same area. In the Lukachukai Mountains, uranium mining on a sizable scale began on Mesa I in 1950, by Sitton and Dulaney Mining Company now Navajo Uranium Company, and on Mesa IV in 1951, by Climax Uranium Company.

The first AEC work in the Lukachukai Mountains was a large drilling project on Mesas I, II, III, and IV (Lukachukai Drilling Project No. 1) during the winter of 1950-51 (Stafford, 1951). Field investigation on Mesas IV, V, VI, VII, and Mexican Cry by John W. King and party extended through the first half of 1951; the results are presented in reports by King (1951), King and Ellsworth (1951), Ellsworth (1951), and Ellsworth and Hatfield (1951). Lukachukai Drilling Project No. 2 was begun in May 1951, and completed in December 1951. A report by Crew and Lowell is in preparation. Field investigation and subsurface study by the writer and party extended from July 1951 to February 1952. Part of the results are presented in reports by Masters (September 1951; October 1951), and Masters and Blum (October 1951; December 1951).

GENERAL GEOLOGY

A knowledge of all the rocks in the Lukachukai Mountains area, their ages, thicknesses, lithologies, and depositional environments is essential to an evaluation of important and, in many cases, debatable factors influencing uranium mineralization. These factors include host rock characteristics, age of rocks and correlation, paleo-environments, unconformities, age of structural movement, age of igneous activity, and Tertiary history and geomorphology related to canyon cutting and ground water movements.

The following discussion of sedimentary and igneous rocks is an assemblage of facts gathered from published material, discussions with other geologists, and personal observations. The assemblage is incomplete, but possibly it may serve as a geologic outline to which more detail can be added by other workers.
Sedimentary Rocks

Paleozoic - Throughout the Paleozoic time, deposition in northeastern Arizona was limited by the positive tendency of the ancestral Defiance Uplift. Approximately 3,000 feet of Paleozoic sediments, separated by several unconformities and primarily of Pennsylvanian and Permian age, accumulated in shallow, marine water while 9,000 feet of marine sediments accumulated 275 miles west in northwestern Arizona (McKee, May 1951). Upper Permian rocks are exposed on the south and east flanks of the Carrizo Mountains where at least 200 feet of Cutler formation red beds are overlain by about 200 feet of massive cliff-forming DeChelley sandstone (J. D. Strobell, personal communication).

Triassic - There is probably no Moenkopi represented in northeastern Arizona but whether that is a result of non-deposition or pre-Shinarump erosion is unknown. According to McKee (October 1951), Triassic sedimentation in this area began with the deposition by north-flowing streams of Shinarump sandstone and conglomerate as the basal deposit of the Chinle formation. The upper part of the Shinarump is exposed in a few creeks south of the Lukachukai Mountains near the Lukachukai Trading Post where total thickness is believed to be about 150 feet. Strobell (personal communication) reports 15 to 20 feet of coarse Shinarump sandstone overlying DeChelley sandstone on the south flank of the Carrizo Mountains and adjacent to the intrusive diorite porphyry. The Chinle crops out extensively on the north and south sides of the Lukachukai Mountains and is about 1,000 feet thick (McKee, May 1951). The lower 200 feet (Chinle "D" of Gregory, 1917) contains sandstone, similar to the Shinarump, and red shale representing deposition by fast-flowing streams. The middle 600 feet (Chinle "C" of Gregory, 1917) consists of red shale and siltstone, and locally abundant fern remains which were deposited by slow moving streams on a swampy flood plain covered by dense, tropical vegetation. The upper 200 feet (Chinle "B" of Gregory, 1917) is red shale and impure limestone which suggests ponding of the sluggish streams. Renewed uplift caused a widespread surface of unconformity at the top of the Chinle (McKee, October 1951) which serves to separate Chinle deposits from Wingate deposits. Most geologists agree that Gregory’s Chinle "A", which lies above the unconformity and is similar in lithology to the Glen Canyon group, rightfully belongs in the Wingate.

Jurassic - The lower Wingate sandstone is composed of about 400 feet of alternating ledges of red eolian sandstone and less resistant units of red fluvialite sandstone. The upper Wingate is a 400-foot cliff-forming, massive, red eolian sandstone. The thickness decreases southward as a result of pre-Carmel erosion across a gentle arch which probably trended northwest from the Zuni Uplift (Wright and Becker, 1951).
Figure 1. Index Map of Four Corners Region
The Kayenta formation which consists of red fluvialite sandstone is 60 feet thick at Rock Point, Arizona, but is truncated by the pre-Carmel unconformity before it reaches the Lukachukai mesas (Wright and Becker, 1951).

The Carmel formation on the Lukachukai mesas consists of about 30 feet of red fluvialite siltstone and stringers of silty sandstone which rest unconformably on the Wingate.

The Entrada sandstone is composed of about 85 feet of red fluvialite sandstone, the upper half of which is fairly clean sandstone-massive, smooth-weathering, and cliff-forming. The lower half of the formation is shaly sandstone, an "earthy" facies, which is probably included in the Carmel by Wright and Becker (1951), but is considered to be Entrada by Strobell (personal communication).

The Todilto limestone consists of platy, lacustrine limestone and minor amounts of limy sandstone. It is about 3 feet thick on the Red Rock monocline and is present on the south side of the Lukachukai Mountains on the Red Rock-Lukachukai road, but pinches out about 3 miles westward.

The Summerville formation consists of about 100 feet of alternating even-bedded red and white banded fluvialite fine-grained sandstone and shaly sandstone.

The Bluff sandstone is commonly considered the basal member of the Morrison formation although in this area, because it is clearly distinct from the overlying Salt Wash and represents a different environment of deposition from any of the Morrison members, most AEC geologists have tended to regard it as a separate formation. On the Lukachukai mesas, the Bluff ranges in thickness from 3 feet at Mesa I to 85 feet at Mexican Cry, and consists of alternating units 1 to 5 feet thick of even-bedded medium-grained fluvialite sandstone and sharply cross-bedded medium-grained frosted very well sorted gray to buff eolian sandstone. A hard white limy sandstone, about 6 inches thick, at the top of the Bluff persists over most of the Lukachukai mesas. The contact with the overlying Salt Wash is relatively sharp and in drill core is easily distinguishable with a hand lens. Together, the Bluff and Summerville generally form a vertical cliff below the Salt Wash sandstone ledges. Drouillard and Jones (1951) report traces of carnolite in Bluff sandstone, west of Sanastee.

The Salt Wash sandstone member of the Morrison formation is carnolite-bearing at numerous localities on the Lukachukai mesas and around the Carrizo Mountains laccolith. Salt Wash stratigraphy on the Lukachukai Mountains is discussed in detail on pages 24 to 30. The regional distribution of the Salt Wash is described in an excellent paper on the Morrison formation by Craig, et al (1951). The discussion of the other members of the Morrison is taken from the same source.
According to Craig, et al. (1951), the Salt Wash sandstone member (see fig. 2) was formed as a large alluvial plain or "fan" by an aggrading system of braided streams diverging to the north and east from an apex in south-central Utah. The major source of the Salt Wash was southwest of south-central Utah, probably in west-central Arizona. The Salt Wash deposits grade from predominantly coarse-textured sediments at the apex of the "fan" to predominantly fine-textured sediments near the margin of the "fan." The Salt Wash has been arbitrarily divided into four facies, the conglomeratic sandstone facies, the sandstone and mudstone facies, the claystone and lenticular sandstone facies, and the claystone and limestone facies. The Salt Wash was derived mainly, if not completely, from pre-existing sedimentary rocks.

The Salt Wash is composed predominantly of interbedded units of sandstone and mudstone. The sandstone is generally fine-grained, quartzitic, limy, cross-bedded, and cliff-forming. The mudstone is commonly silty or sandy, red to gray in color, and forms steep slopes between the sandstone ledges.

The Lukachukai Mountains, immediately south of Cove, are situated on the southern edge of Salt Wash deposition within the sandstone and mudstone facies. Thickness of the Salt Wash in this area ranges from 100 to 150 feet.

The Recapture shale member of the Morrison is about 400 feet thick on the Lukachukai Mountains and consists of interbedded, fine- to medium-grained sandstone and mudstone. In general, the Recapture is less resistant than the Salt Wash and forms a slope above the Salt Wash ledges. The Recapture was derived from a source area to the south composed of sedimentary, igneous, and metamorphic rocks, and was deposited by "an aggrading system of braided streams" (Craig, et al., 1951). Traces of carnotite mineralization in the Recapture have been found on the Lukachukai Mountains, and Drouillard and Jones (1951) describe carnotite mineralization in Recapture sandstones about twelve miles to the southeast near Sanastee, New Mexico (Geologic Map, pl. 1).

The Westwater Canyon sandstone member of the Morrison is about 250 feet thick on the Lukachukai Mountains and consists principally of fine to coarse-grained sandstone. It was derived from the same source area as the Recapture and deposited by the same type of streams (Craig, et al., 1951).

The Brushy Basin shale member of the Morrison is about 100 feet thick in the area of the Lukachukai Mountains (Craig, et al., 1951) although apparently it was stripped off the mountains by pre-Pliocene (?) erosion. The Brushy Basin consists of variegated mudstone with scattered lenses of sandstone. The sediments were deposited in lacustrine and fluviatile environments (Craig, et al., 1951).
Claystone and lenticular sandstone facies
Claystone and limestone facies
Sandstone and mudstone facies
Concretionary sandstone facies

Contour interval 50 feet

Isopachous and facies map of the Salt Wash sandstone member of the Morrison formation.
Cretaceous - No Cretaceous deposits are now present on the Lukachukai Mountains as a result of the Tertiary unconformity, but a complete Cretaceous section is exposed to the east on the west flank of the San Juan Basin. It is probable that a normal thickness of Cretaceous rocks was deposited across the Lukachukai Mountains. Sections measured by Pike (1947) along the San Juan River about 30 miles northeast of Cove give detailed information about the Cretaceous deposits up to the top of the Mesa Verde Group.

The Dakota sandstone is about 300 feet thick and consists of a highly variable sequence of lenticular sandstones, shales, and coal measures. Most of the Dakota represents floodplain, swamp, and lagoonal environments, except the uppermost beds which are littoral and represent the basal deposits of the transgressing Mancos sea. The lower part is probably Lower Cretaceous whereas the upper part is Upper Cretaceous (Pike, 1947).

The Mancos shale is approximately 2,000 feet thick and consists of gray marine carbonaceous shale (Pike, 1951). About 800 feet above the base of the Mancos is the Tocito sandstone member, about 25 feet thick, which is weakly mineralized with carnitite at Beautiful Mountain (P. C. Ellsworth, personal communication).

The Mesa Verde Group is about 1,600 feet thick and contains lenticular sandstone, carbonaceous shale, and coal measures representing complex changes in environment from marine to continental types (Pike, 1947). Post-Mesa Verde Cretaceous rocks of both continental and marine types attain a thickness of about 3,000 feet on the northwest side of the San Juan Basin (Silver, 1951).

Tertiary - Rocks of Tertiary age are represented by the Tohatchi shale and the overlying Chuska sandstone, the two formations aggregating more than 1,000 feet of thickness and lying unconformably on Mesozoic rocks. No diagnostic fossils have yet been found in these formations, although they are clearly of Tertiary age as shown by their unconformable position on both the Defiance monocline, a Laramide structure (Kelley, 1951) and the Lukachukai monocline, a probable Laramide structure.

Gregory (1917) says that in places on the Chuska Mountains the lava flows have "the appearance of being interbedded with" the Chuska sandstone, but that other field observations indicate that the lava is younger. The lava is probably of Pliocene age (see below), hence the sediments are Pliocene or older. Comparison of the vertical position of the Tertiary rocks of the San Juan Basin and the Chuska Mountains sheds some light on the problem of age of the Tohatchi and Chuska. The youngest rocks in the central San Juan Basin are eocene (San Jose formation) at an elevation of about 7,000 feet. The base of the Tertiary on the Chuska Mountains is about 8,000 feet in elevation. It is improbable that there was any differential uplift of the two areas during Tertiary, hence the elevation of the Tertiary rocks on the Chuska Mountains suggests a younger age for
those rocks than for the eocene rocks of the basin. Oligocene was, in general, a time of erosion. Thus, the Tohatchi and Chuska are more probably Middle to Upper Tertiary in age, i.e., Miocene or Pliocene.

Deposition of the Tertiary sediments followed a period of intense erosion which stripped over 7,000 feet of Cretaceous rocks, a maximum of 1,800 feet of Jurassic and Triassic rocks, and all pre-existing Tertiary rocks. The base of the Tertiary apparently represents a fairly uniform plain of erosion; the present-day elevation is about 8,000 feet by several rough measurements. Along the Lukachukai "monocline" (see section on Structure, below), the erosion surface cuts progressively older rocks as far down as the lower Wingate in a southeasterly direction up the rising axis of the structure. From the mountain projection east of Cove and Mesa I southward across the Lukachukai Mountains all Salt Wash rocks were removed (fig. 6 and pl. 1).

The Tohatchi shale is about 200 feet thick by rough estimate, and consists of fine-grained soft fluviatile and lacustrine sandstone, clay shale, and layers of bentonite 1 inch to 1 or 2 feet in thickness.

The Chuska sandstone is about 800 feet thick and consists of fine-to medium-grained, quartzose, siliceous to unconsolidated, clean to bentonitic, eolian and fluviatile sandstone. The upper 200 feet of Chuska forms a very hard, siliceous cap on top of the mountains. H. E. Wright (personal communication) attributes the silica cement to volcanic intrusions.

Regional upwarping of the vast Colorado Plateau and initiation of the Canyon cutting cycle is generally dated late Pliocene (Eardley, 1951). Thus, elevation of the Lukachukai Mountain area probably began shortly after deposition of the Chuska in Pliocene (?) and probably accompanied magmatic intrusion. Ground water began to circulate at that time.

Igneous Rocks

The igneous rocks of the Lukachukai Mountains area have been studied by Emery (1916), Gregory (1917), and Williams (1936). Some of the results of their work are discussed in this section.

Basalt-type rocks - A field study of igneous rocks by Williams (1936) extends from the Hopi Buttes volcanic field east across the south end of the Defiance Uplift to the Chuska Mountains, north to Red Rock Valley, and west to Monument Valley. Williams did not study the Carrizo laccolith in detail. The Hopi Buttes volcanics are dated Middle to Upper Pliocene by a mammalian fauna in the Bidahochi lake beds which are interstratified with the volcanics. Basaltic-type dikes, sills, plugs, and flows, quite similar to the Hopi Buttes rocks, extend northward through the Chuska Mountains to the Red Rock Valley with the chemical composition increasing gradually in potassium—
probably as a result of the increased amount of granitic inclusions (Williams, 1936). The total amount of flow rock decreases to the northward and only one flow has been recognized in the Lukachukai Mountains. The flow is on the northeast side of the mountain projection east of Cove (Gregory, 1917). Williams (1936) says, "There is, however, no reason for doubting that the Navajo volcanoes were active at the same time as those of the Hopi Buttes; namely, during the Middle and the Upper Pliocene."

Williams (1936) states that intrusion in the Chuska Mountains and Red Rock Valley followed a random pattern, hence, shows no consistent lineation. This is true within any small area; but the author suggests that the general limitation of intrusions to the north-trending Chuska Mountains and Red Rock Valley plus a few that occur eastward as far as the Hogback monocline, may indicate a relation to the north-trending Defiance monocline and associated structures like the Hogback. Williams (1936) mentions a similar situation in Monument Valley where the intrusions are apparently related to a strong system of joints normal to the Comb Ridge monocline. The monoclinic structures conceivably represent a zone of weakness or faulting at depth (see discussion of structure below).

The flow rock is classified as trachybasalt, a basalt-type rock high in potassium. The dike and sill rock are of similar composition but are classified as minette (Williams, 1936). One small dike is intruded into the Salt Wash sandstone member at Mesa I about 300 yards north of the mining camp. A large sill, intruded into the Chuska sandstone is exposed on the mountain projection east of Cove. Dikes intruded into the Chuska sandstone support several of the high peaks on the mountains a short distance east of Mesa I and apparently east of the eroded edge of Salt Wash rocks truncated by the Tertiary unconformity. Several small dikes are exposed in Red Rock Valley where they intrude the Chinle formation. Thumb Rock near the Red Rock Trading Post and Big Plug on the southeast flank of the Carrizo Mountains are volcanic plugs intruded into Jurassic rocks. The plugs are composed of tuff breccia cut by stringers of minette lava.

Laccolithic rocks - Emery (1916) described the intrusive diorite porphyry laccolith of the Carrizo Mountains which has a surface diameter of 7 to 10 miles. The rock is composed of phenocrysts of plagioclase and hornblende in a groundmass of quartz and orthoclase. Williams (1936) suggested that the deformation of surrounding strata and the negligible amount of contact metamorphism indicated a rock which was originally highly viscous and low in volatiles.

Magmatic differentiation related to age determination - The author discussed the problem of minette intrusives adjacent to diorite porphyry intrusives with Dr. E. E. Wahlstrom who suggested that the two rock types most likely are differentiation products of the same magma and were probably intruded into the sedimentary rocks at approximately the same time. If that is true, and Williams' (1936) dating of the volcanics is accepted, then the Carrizo laccolith is of Pliocene age. It is of certain Tertiary
age because the intrusive cuts across Laramide structure at the northeast and northwest corners of the mountains (pl. 1).

**Source of hydrothermal solutions** - Contact metamorphism adjacent to all the igneous rocks resulted in only slight baking of the sedimentary rocks for a few inches, with one exception in the East Carrizo area where a plug causes extensive alteration for several hundred yards. Gold, silver, and copper, in small amounts, are reported from the Carrizo Mountains (Bill Peters, personal communication), but it is apparent from the igneous-sedimentary contact that there was only a small quantity of mineralizing solution available from these relatively "dry" injections. Advocates of a hydrothermal source for the uranium in this area should not suggest the dikes and laccoliths as the source of mineralization, but should point to the large subsurface magma body which fed the many intrusions and extrusions of the area. In the opinion of Dr. Wahlstrom (personal communication) igneous bodies exposed today have never been proven to be the main sources of hydrothermal, mineralizing solutions. Such solutions moved upward from the subsurface magma bodies, not outward from their small-scale surface exposures.

**Structure**

**Regional setting** - The Lukachukai Mountains, which constitute the north end of the Chuska Mountains, are capped by Tertiary sandstone. The mountains are located on the northeast flank of the Defiance Uplift (fig. 3) which is a large asymmetric anticline bounded on the east side by the steep-dipping Defiance monocline and on the west by a gentle homoclinal dip. The great synclines which compliment the Defiance anticline are San Juan Basin on the east and Black Mesa Basin on the west. Ten miles north of the Lukachukai Mountains is the Carrizo Mountain laccolith. The strata are arched around the flanks of the Carrizo intrusion (pl. 1) and attain dips of 20 to 25 degrees. Big Plug, a minette intrusion south of the Carrizos and west of Red Rock, also causes arching. At the northeast and northwest edge of the laccolith, west-striking Jurassic rocks are cut by the intrusion. Thus, the time of intrusion and arching of strata around the laccolith clearly postdates the north to west trending structure associated with the Defiance upwarp.

Fifteen miles south of Beautiful Mountain, near Toadlena, the north-trending, east dipping Defiance monocline splits into two parts. The western monocline diverges in strike to the northwest and retains the name Defiance. The eastern monocline diverges in strike to the northeast and receives the name Hogback Mountain or Hogback monocline, and is generally considered the rim of the San Juan Basin. North of Beautiful Mountain, the Defiance or western monocline turns northward and splits again into two north-trending structures, the Red Rock monocline and the Dakota or Tacita monocline, which are separated by a structural platform. Maximum dip on both flexures is about 15 degrees to the east. Westward from the north-trending monoclines, across the north front of the Lukachukai Mountains,
GEOLOGIC MAP OF THE FOUR-CORNERS REGION

FIG. 3
the strata gradually assume a northwest strike and gentle northeast dip conformable with the structural trend around the northeast flank of the Defiance anticline. Domesing of strata around the Carrizo intrusion was superimposed on the pre-existing structural trends.

The Lukachukai "monocline" is a northwest-striking flexure which, for a distance of about eight miles, causes a sharp reversal of 10 to 30 degrees in the gentle northeast dip off the Defiance anticline. Actually, as shown by the structure contours (pl. 2), the "monocline" is a sharply asymmetrical, northwest-plunging anticline, but the abrupt dip reversal and straight line axis of the structure fit more closely the connotation, if not the definition, of the term monocline.

Age of structures—The time of major structural movement in this region can be dated as late Cretaceous on the west side of the San Juan Basin to late Eocene in the central part of the basin by the unconformable contacts of Cretaceous, Paleocene, and Eocene rocks (Kelley, 1951). Thus, Laramide movement of the Defiance Uplift, a complementary structure to the San Juan Basin, can be dated late Cretaceous to early Eocene by analogy. The age of the Lukachukai monocline is not so clear because, as a minor feature, it is not necessarily related to the San Juan Basin as is the Defiance Uplift. The Lukachukai monocline is pre-Tohatchi and probably Laramide in age.

Cause of structures—The Lukachukai monocline is characterized by abrupt change in dip, straight line axis, and complete lack of secondary folds either on or parallel to the axial trend. These characteristics are common to most monoclines on the Colorado Plateau. To the geologist familiar with true compressional structures like the anticlines of the Rocky Mountain province, the structure contour pattern of the monoclines here is more indicative of faulting than of folding. In fact, some of the Plateau monoclines are related to faults which can be seen at the surface. For example, the monoclines on both the northwest and southeast sides of the Uncompahgre Uplift can be seen to overlie major normal faults or fault systems in the basement rock. The East Kaibab monocline of the Kaiparowits region in south-central Utah overlies a normal fault (Gregory and Moore, 1931). These monoclines are similar to most of those on the Plateau such as the Waterpocket Fold, Comb Ridge, etc., which are impressive in their surprisingly straight and long distance continuation across thousands of square miles of relatively undisturbed strata. Such a pattern is not typical of compressional structures and suggests draping of the sediments over normal faults in the basement rock (fig. 4). Other monoclines such as the Defiance and Nacimiento monoclines on the west and east sides of the San Juan Basin are adjacent to large basins which either initiate or are related to compressional forces (Fanshawe, 1947). The geologic map of the San Juan Basin (Silver and Hoover, 1951) indicates strongly that the Nacimiento monocline represents a northward extension, at depth, of the Nacimiento thrust. It seems probable that the Defiance monocline may also represent a high angle thrust fault at depth.
Fig. 4—Monoclinal structure related to faulting in the basement rock and draping of surficial sediments.

The possible existence of subsurface faults (either thrust or normal type) underlying the numerous monoclines of the Plateau is of primary importance to a discussion of the probability of an ultimate hydrothermal source for the Plateau uranium ores and is considered in another section in more detail.

Uranium Deposits

The geologic map (pl. 1) shows the known uranium deposits in the Lukachukai Mountains area. All deposits are in Salt Wash sandstone except for a small amount of Recapture mineralization at two localities, and traces of mineralization in the Tocito and the Bluff at separate localities. The mineralogy and size of the deposits, which are similar over the entire area, are discussed in the section about ore deposits on the Lukachukai mesas.

Several large mines and numerous mineralized outcrops are located on the east side of the Carrizo Mountains along the Red Rock monocline. An AEC drilling project is scheduled to begin immediately in the East Carrizo district and the area is under study for further drilling recommendations. Mines and outcrops equal in value to those of the East Carrizo district are located on the west flank of the mountains with an especially dense concentration along the Battlesnake monocline. Patches of Salt Wash on the north and south flank and on top of the intrusion are also mineralized. As mentioned previously, 15 to 20 feet of Shinarump sandstone is exposed for a total distance of about three miles along the south edge of the Carrizo laccolith, but is not mineralized (J. D. Strobell, personnel communication).

Midway between the Carrizo Mountains and the Lukachukai Mountains, and slightly west, ore grade mineralization occurs at Cove, Kinustia, and Alcove Mesas. Cove Mesa was drilled by the AEC in the winter of 1950-51 and several small ore bodies were discovered (Garza, 1951) 1/.

1/ See Appendix C (1), for exact figures.
Ore grade carnitite deposits in the Lukachukai Mountains are located on and between Mesas I and V on the northeast rim of the mountains and on and between Dry Bone and Camp Mesas on the southwest rim. Mesas to the northwest of the mineralized belts on the northeast and southwest rims of the mountains have only scattered traces of carnitite in the Lukachukai Mountains (Masters, 1951). Two AEC drilling projects on the northeast rim have discovered a number of ore bodies (Stafford, 1951; Crew and Lowell, in preparation). A drilling project on the southwest rim is scheduled to begin in a few months.

AEC bulldozer work nine miles west of Sanastee discovered mineralization in the Recapture member of the Morrison (Droullard and Jones, 1951). This Recapture deposit is on the Defiance monocline south of the limit of Salt Wash deposition.

Vanadium mineralization is present rather continuously for about five miles in Salt Wash sandstone on the Red Rock monocline south of Red Rock.

Traces of carnitite mineralization have been found by Ellsworth (personal communication) in the Tocito sandstone member of the Mancos shale on Beautiful Mountain. Traces have also been found in the Bluff sandstone west of Sanastee by Droullard and Jones (1951) and in the Recapture at Mesa I and Three Point Mesa on the Lukachukai Mountains by the author.

No mineralization has been reported from the thick, conglomeratic Shinarump which covers broad areas of the Defiance Uplift.

Summary of General Geology and Interpretation of Geologic History

About 3,000 feet of Paleozoic sediments, separated by several unconformities, accumulated under shallow marine water in the area of the Lukachukai Mountains. During the Triassic and Jurassic periods the area was above sea level and received another 3,000 feet of fluvialite, lacustrine, and eolian sediments which were deposited under environmental conditions ranging from tropical to arid. The Salt Wash sandstone member, which was deposited as a large alluvial fan by streams flowing north and east from a source in west-central Arizona, is of primary interest because it carries most of the uranium deposits. An important unconformity at the base of the Carmel formation, resulting from uplift along a northwest-trending axis, caused removal of approximately 200 feet of middle Jurassic sediments.

During the Cretaceous period, marine seas advanced southwest across the area which sank rapidly and received about 7,000 feet of sediments.

Laramide deformation along the east side of the Defiance Uplift began in late Cretaceous and probably extended into the Eocene, resulting in the Defiance monocline, the subsidiary Red Rock and Dakota monoclines, the

1/ See Appendix C (2), for exact figures.
northwest structural trend across the Lukachukai mesas, and probably the Lukachukai monocline. The monoclines may be the result of surficial sediments draped over normal or reverse faults at depth.

Early Tertiary depositional history in the area is unknown, but it is clear that prior to deposition of the Tohatchi shale all of the Cretaceous and early Tertiary deposits were eroded from the Lukachukai Mountains. The Tohatchi and Chuska formations comprise over 1,000 feet of fluviatile, lacustrine, and eolian sediments admixed with considerable volcanic ash. Comparison by position with the Tertiary rocks of the San Juan Basin suggests that the Tohatchi and Chuska are Miocene or Pliocene.

Intrusion and extrusion of minette and trachybasalt in numerous plugs, dikes, sills, and flows occurred during or shortly after deposition of the Tohatchi and Chuska. Intrusion of the Carrizo laccolith of diorite porphyry probably took place at the same time; the porphyry is thought to be a differentiate of the same parent magma responsible for the basalt type rock.

Regional upwarping of the Colorado Plateau is tentatively dated late Pliocene (Eardley, 1951) which correlates with the tentative dating of magma movement. The late Tertiary upwarping initiated the beginning of ground water circulation and the "canyon-cutting cycle" which is responsible for present topography.

Conditions at the end of Pliocene appear to have been as follows (fig. 5): The Defiance and Lukachukai monoclines had been formed by Laramide orogeny, truncated by early Tertiary erosion, and then covered by Tohatchi and Chuska sediments. Igneous intrusions in the form of a laccolith and numerous small dikes and plugs had accompanied the early stages of regional uplift, but ceased by late Pliocene. Ground water had begun to circulate.

Land surface elevations were still lower than they are today because regional uplift is known to have continued through the Pleistocene (Feneman, 1931). Isolated plugs and dikes east of the cross-section (fig. 5) protruded above the relatively flat land surface across the Lukachukai Mountains, and consequent streams were beginning to cut into the sediments as a result of uplift. In conformity with structure, the land surface extended fairly evenly across the present Red Rock Valley to a pronounced dome over the Carrizo laccolith which, like Navajo Mountain today, had not yet been exposed. The Lukachukai Mountains were not topographically high; they exist today as an erosion remnant because the Chuska cap rock was silicified in this area by igneous intrusions (H. E. Wright, personal communication).

During Pliocene, elevation of the Salt Wash on top of the Lukachukai monocline was probably somewhat lower than its elevation on top of the Carrizo laccolith. Patches of Salt Wash are reported at about 9,000 feet on top of the Carrizo's but maximum elevation of the Salt Wash on the Lukachukai Mountains is 7,900 feet, at Mexican Cry. Presumably, uplift during Pleistocene did not
change relative elevations of the strata. Across Red Rock Valley the Salt Wash was within 750 to 1,500 feet of the surface, depending on the thickness of Tohatchi and Chuska, because younger Mesozoic rocks had been eroded. East of Mesa I, no Salt Wash remained because Tertiary erosion cut deep into the lower Wingate. It is apparent that within a poorly defined area near Cove, north of Mesas I and II and east almost to the Red Rock monocline, the Salt Wash was removed by erosion. Salt Wash sediments on the west side of the area were not removed as shown by exposures on top of the monocline at Mexican Cry. Thus, at the end of Pliocene and also during the time of igneous intrusion, the Salt Wash of the western Lukachukai mesas extended continuously across the present valley to the Carrizo laccolith.

Hence it was possible for ground water collecting on the Carrizo Mountain dome to enter Salt Wash sandstones and, by hydrostatic pressure, move outward several miles farther than the southwest rim of the present Lukachukai Mountains. This condition existed until sometime during Pleistocene when erosion began to dissect the Salt Wash.

Carnotite ore deposits occur in Salt Wash sandstones around the flanks of the Carrizo Mountains, on several mesas to the south and west, and on the eastern mesas of the Lukachukai Mountains. Small amounts of carnotite ore occur in Recapture sandstone west of Sanastee on the Defiance monocline. Traces of carnotite have been found in the Bluff sandstone and the Tocito sandstone.

GEOLOGY OF THE LUKACHUKAI MESAS

This discussion presents most of the work done on the Lukachukai mesas by the author and field partners, hence is divisible from the first section of the paper which summarizes mainly the findings of other geologists who have studied the area of the Lukachukai Mountains.

Ore Deposits

Ore grade uranium deposits are considered by the AEC to contain one foot of 0.10% U₃O₈ or the equivalent of higher grade and less thickness. Vanadium deposits equivalent to one foot of 1% V₂O₅ are included in ore tonnage estimates. The deposits consist
mostly of limy, fine-grained sandstone impregnated with carnotite and vanoxite. Ore minerals are the same throughout the area. Carnotite \((K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 3H_2O)\) is the predominant uranium mineral. It occurs as finely disseminated yellow flakes in sandstone, as a coating on fractures and mudstone surfaces, and as a replacement of carbonaceous material. Vanoxite \((2V_2O_4 \cdot V_2O_5 \cdot 3H_2O)\) is the common gray, micaceous vanadium mineral which coats the sand grains and gives a gray color to the host rock. Pintadoite and pascoite, green and orange calcium vanadates, are present on a few exposed rock surfaces. Several other calcium vanadate minerals occur in the mines, in addition to a mineral identified only as "black uranium oxide" (King, 1951).

The ore bodies show considerable variation in size and shape, as in all other areas. The long dimensions of the largest ore bodies discovered by drilling are about 500 feet. Rim outcrops of ore grade rock are commonly 100 feet or more long. The deposits are tabular and seldom exceed 3 to 4 feet in thickness; grade averages about 0.30% \(U_3O_8\).

All known uranium deposits on the Lukachukai mesas are indicated on Figure 6. The map shows two discontinuous belts of mineralization, one across the northeastern mesas from I to V, and the other across the southwestern mesas from Camp to Fall. (No ore grade mineralization occurs on Fall or Step Mesas.) Mineralization does not extend northwest from the belts outlined above, with the exception of negligible traces at half a dozen widely separated localities. There is no reason to believe that mineralization does not extend under the Lukachukai Mountains between the known ore belts. Therefore, a general north to northeast ore trend crosses the eastern Lukachukai mesas.

Development of the several large, high grade deposits and numerous smaller ones on the southwest rim has not yet begun, so detailed information about those deposits is not available. It is anticipated that the deposits will be comparable in size, or larger, than the better known deposits on the opposite side of the mountains (Masters, 1951).

Mesas on the northeast rims have been intensively explored by a total of 140,000 feet of AEC drilling, and considerable bulldozer stripping and mine development by private interests. To illustrate the comparative amounts of ore discovered on each mesa by both drilling and mining (mining figure counts only tonnage that has been shipped), a "value factor" reflecting tonnage and grade is shown in Table 1.1/

<table>
<thead>
<tr>
<th>Mesa</th>
<th>Grade Grade</th>
<th>Value Factor</th>
<th>U:V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>.36 (U_3O_8) .80 (V_2O_5)</td>
<td>21</td>
<td>1:2</td>
</tr>
<tr>
<td>IV(\frac{1}{2})</td>
<td>.30 1.26</td>
<td>11</td>
<td>1:4</td>
</tr>
<tr>
<td>V</td>
<td>.18 1.31</td>
<td>5</td>
<td>1:7</td>
</tr>
</tbody>
</table>

Table 1—Mineralization on three of the Lukachukai Mesas

1/ See Appendix C (4), classified as Restricted, for exact figures and an explanation of the "value factor."
Mesa I contains more known ore than Mesa IV, which in turn contains more known ore than Mesa V. The uranium-vanadium ratio on Mesa I is 1:2, on Mesa IV is 1:4, and on Mesa V is 1:7. The increasing vanadium content with decreasing total uranium-vanadium tonnage checks with field observations that high grade carnottite and high grade vanadium are seldom found together. Most "rolls" in this area are dark gray and high in vanadium with lesser amounts of carnottite streaks and pods; the mineralization is commonly associated with clay seams or galls and bits of carbonaceous matter. In general, the highest grade carnottite deposits are rather evenly disseminated as yellow flakes and specks in fairly clean, light tan sandstone. Specifically, about 90 individual occurrences of weak to ore-grade mineralization, ranging from a few inches to several feet in thickness are recorded on the Mesa V core logs. Approximately 40% of the occurrences, a few of ore grade, are associated with carbonaceous flakes or seams; about 30% of the occurrences, some of ore grade, are associated with mudstone seams, splits, or galls; the other 30% of the occurrences, including most of the high grade ore, occur in relatively clean sandstone. In the Mesa IV core logs, about 120 individual occurrences were noted. Approximately 30% were associated with carbon; 35% were associated with mudstone; and 35%, including most of the high grade ore, were in relatively clean sandstone.

Structure and Ore Deposits

Structure contour map - A detailed structure contour map (pl. 2), drawn with a 20-foot contour interval on the Bluff-Salt Wash contact, was constructed from surface and subsurface control. Part of the mapping was done by other field parties (Stafford, 1951; King, 1951; Ellsworth and Hatfield, 1951; King and Ellsworth, 1951; and Ellsworth, 1951). For use of future workers on these mesas, the method of mapping is discussed in Appendix A. Reliable elevation markers are shown on the map and a description of the location of each marker is given in Appendix B written by R. D. Blum.

The Bluff-Salt Wash contact is an excellent marker for structural mapping at the scale used on this map, i.e., 20-foot contours drawn on points about 500 to 1,000 feet apart on a horizontal scale of 1" = 500'. The nature of the contact, which is both gradational and erosional may not lend itself to much more detailed mapping in certain areas. At one place on the west side of Mesa II, Bluff-type sandstone was observed to grade indistinguishably into Salt Wash-type sandstone through a vertical distance of five feet. Several cores showed the same gradation for a few feet. A similar relation is seen on the south edge of Two Prong Mesa where only a small amount of upper Salt Wash sandstone was deposited, the lower Salt Wash interval being occupied by about 40 feet of Bluff-type, eolian sandstone which intertongues with Salt Wash sandstone along the east and southwest rims of the mesa.

All geologists in the area have noted at the top of the Bluff, a white liny clean quartzose fine- to medium-grained sandstone which persists over the mesas. The same type of liny sandstone occurs at the top of the Bluff.
EXPLANATION
- Ore Hole
- Mineralized Hole
- Barren Hole

Drill holes not located within ore bodies are not shown.

Indicated Ore Deposit
Inferred Ore Deposit

NOTE
MAP TAKEN FROM REPORT
BY H.S. STAFFORD 1951.
at King Tutt Mesa, East Carrizo district. It is difficult to imagine a continuous six-inch to three-foot thick sandstone bed over the entire region, even over the Lukachukai mesas, considering the obvious fluviatile environment of most or all of the Salt Wash and the very limited continuity of all beds studied in detail. A continuous stratum might accumulate in a large lake, but the resulting sediments would not be composed of fine- to medium-grained sandstone. An answer seems to lie in the fact that Salt Wash sandstones are above average in their content of CaCO₃ cement and it is probable that downward percolation of lime-saturated ground water would cement the top several inches to several feet of the Bluff sandstone, regardless of the minor irregularities in the Bluff-Salt Wash contact. Thus, the limy sandstone does not represent a perfectly continuous horizon for structure mapping.

The Lukachukai "monocline" is actually a sharply asymmetric, northwest plunging anticline adjacent to a northwest plunging syncline (pl. 2). The Salt Wash-Bluff contact dips gently northeast at an average angle of 1⅔ degrees across the Lukachukai mesas to the northeast rim where the dip is sharply reversed to an angle of 14 degrees southwest on Mesa VII, slightly less on Mexican Cry, and slightly more on mesas to the east. On the eastern mesas, most of the southwest-dipping Salt Wash has been eroded off, but the Wingate outcrop shows that southwest dip does increase on those mesas.

The plunging anticlinal axis of the structure trends about N. 40 W. toward Mexican Cry where it swings abruptly northward; within one mile at East and West Mesas (pl. 1), the axis turns northeastward and dies out. The southeastward termination of the anticline is covered by Tertiary sediments, but the anticline rather clearly "opens up" and blends into the homoclinal dip off the Defiance Uplift (pl. 1).

The plunging synclinal axis follows much the same pattern, trending northwest across the mesas and losing its identity beyond Mexican Cry. The structure contour map (pl. 2) shows a pronounced change in the rate of axial plunge across the mesas. From Mesa I to the east edge of Mesa V, the axis drops an average of 1.69'/100': a dip of 54 feet. From the east side of Mesa V to the west side of Mexican Cry, the axis drops an average of 0.2'/100': a dip of 8 feet, which is only 1/7 of the dip from Mesa I to Mesa V. Across the central part of Mesa VII, the synclinal axis is almost completely flat.

Hypothesis of structural control of ore deposition - The hypothesis of structural control of uranium ore deposits has received considerable attention from many competent geologists and was thought by the first workers in the area to apply to the Lukachukai deposits. King (1951) reasoned that a considerable amount of water reaches the Salt Wash by downward percolation where it leaches and transports carnotite as shown by efflorescences on fresh surfaces. On the Lukachukai Mountains, the logical course of ground water would be downward dip toward the mesas on the northeast rim. The moving ground water would leach deposits under the mountains and on the southwest rim, follow the most permeable sand lenses toward the northeast, and eventually "stagnate," or slow down,
in areas where structural dip flattened or reversed. Theoretically, the best trap would be at the bottom of the syncline, particularly where the synclinal axis flattens out across Mesas V, VI, VII, and Mexican Cry. King suggested that the original ore trend was northeast and the ore bodies were enriched and redeposited, or re-oriented, in favorable structural situations.

A northwest ore trend related to structure was postulated for all ore bodies discovered by drilling Mesas I, II, III, and IV, as shown in figure 7 (from Stafford, 1951). To maintain a northwest trend, several of the ore bodies are drawn through barren holes or weakly mineralized holes. Several other ore bodies show considerable elongation without any drill hole control.

The map (pl. 2) shows only a few minor irregularities in structural strike and dip, other than the main reversal in dip and the variation in dip of the synclinal axis. The dips flatten gradually as the synclinal axis is approached. Areas of such flattening are preserved on Mesa V where there are several large ore bodies within the flattened area, on Mesa VI where there are two negligible carnotite outcrops in the flat, and on Mesa VII and where no trace of mineralization has been found in the structural flattening which covers an area more than three times as large as the flattened area on Mesas V and VI. The dip at Mesa IV½ in the vicinity of the large ore bodies apparently steepens slightly on the down-dip side of the ore bodies, but there is no flattening of dip at the ore bodies. The ore bodies at Mesa I seem to lie, in part, on slightly steeper dip than does the relatively barren Salt Wash on the northwest end of the mesa. The small ore bodies on Mesa IV are not associated with any apparent dip change. Large quantities of ore on the southwest rim (fig. 6), probably equal in tonnage and grade to deposits on the northeast rim, are about three miles updip and apparently isolated from control by the Lukachukai syncline.

Figure 8 shows a detailed structure contour map of Mesa V, drawn on five-foot contour intervals. The theoretical axes of each ore body are indicated by arrows. There is no dominant lineation trend of individual ore bodies. The major ore bodies do fall on a northwest line, but the pattern is caused by stratigraphic control, as will be shown in the next section of this report.

At the time the structure hypothesis was proposed, the large, high grade deposits three miles updip on the southwest rim were relatively unknown, and proximity of the then known deposits to the Lukachukai syncline naturally dominated all theories concerning ore localization. Another contributing factor was the lack of any other plausible theory of ore concentration; little was known a year ago about stratigraphic traps in the Salt Wash.

Bain (1951) expressed general agreement with the hypothesis of structural re-location of ore deposits and stated that increased dip ("declevity") reduced the "importance of the structure." He further stated, with reference to the Lukachukai mesas, that "every case of mineralization with about 0.01% U₃O₈ is on the gentle limb and ore fails to cross the synclinal axis north
of Mine 23." Actually, there are but a few hundred yards of Salt Wash outcrop north of Mine 23 on Mesa I. The one small carnotite outcrop on Mesa VII assays 0.23% \( \text{U}_3\text{O}_8 \) (Ellsworth and Hatfield, 1951) and occurs in sediments dipping 14 degrees southwest. Large ore deposits in the region occur on steep dips, such as the Syracuse Mine on the east side of the Carrizo Mountains with 10 degree dip, and the Rattlesnake mines on the west side of the mountains which lie predominantly on the steep side (6 degree dip) of the Rattlesnake monocline (Stokes, 1951). Deposits near Sanastee dip 9 degrees. Bain (1951) also said "Drilling at Mexican Cry at the west end of the structure was principally on the steep limb and even intensive and closely spaced drilling failed to disclose any visible uranium mineralization east and north of the synclinal axis." Actually, only six holes spaced 500 to 1,000 feet apart were drilled on the steep limb; 42 holes were drilled on the gentle limb and along the axis of the syncline. No mineralization was found.

Structural traps do not represent the major control for the uranium deposits on the Lukachukai mesas. The present maps are not detailed enough to indicate any minor reorientation of the ore bodies, but certainly there has been no mass migration toward the Lukachukai syncline, nor has there been mass reorientation toward the northwest. More facts supporting these statements will be presented in the following section.

The author has felt it necessary to review and criticize the structural trap hypothesis applied to the Lukachukai mesas because other writers (Bain, 1951, and Dodd, 1951) have referred to the Lukachukai area as though it constituted a proved example of structural trapping.

The idea that structure can provide a trap situation is not necessarily invalid, but on the Lukachukai mesas structures as strongly developed as the Lukachukai syncline were not so important as the stratigraphic features discussed below.

**Stratigraphy and Ore Deposits**

**Surface stratigraphy** - The importance of stratigraphy to the control of ore deposition has been suggested by several writers. In the final Union Mines report, Weber (1947) presented a lithofacies map of sandstone percentage which showed a relation of 40 to 60% sandstone areas with known Salt Wash carnotite deposits. Bain (1951) said:

"The carnotite deposits occur where shale makes up about half of the stratigraphic section of the Salt Wash member. Under these conditions, these impermeable beds are capable of guiding the artesian flow and inhibiting unlimited percolation. . . . . . If new extensions are to be sought, the rule of shale presence should be adhered to with diligence."

Dodd (1951) agreed with Bain and emphasized that the number of individual shale beds, as well as the percentage of shale, is important in canalizing solution flow; a section composed of 50% shale, evenly distributed, would be relatively impermeable.
A significant variation in shale content of the Salt Wash across the Lukachukai mesas was first recognized by the change in outcrop characteristics. Massive sandstone cliffs on the western mesas give way to distinct sandstone ledges separated by dirt- and brush-covered slopes on the eastern mesas. The slopes are formed on mudstone or interbedded thin layers of sandstone and mudstone, both of which are impermeable and therefore have the same effect on solution flow. To depict quantitatively the stratigraphic change, numerous surface sections were measured on most of the mesas and compared with core logs and gamma logs. Representative sections, either surface or subsurface, were chosen from each mesa and simplified to show only sandstone and mudstone or interbedded units. The sections are presented on Figure 9; the line of section and plan view of the facies relationship are on Figure 6.

As shown on the cross-section, the Salt Wash at Mexican Cry is about 135 feet thick and consists of about 90% sandstone, abundant clay galls, and persistent lenses of granule conglomerate in the lower part of the section. Two, and possibly three, thin mudstone zones occur within the sandstone. Traces of carnotite are present. At Mesa VII, the lithology is approximately the same: a 130-foot thick section contains about 85% sandstone with abundant clay galls, and persistent lenses of granule conglomerate in the lower part; four mudstone zones and traces of carnotite are present. The thick sandstone facies continues across Mesa VI, but a marked change occurs at Mesa V. The total section at Mesa V is 115 feet thick and contains only 70 to 75% sandstone, at least six mudstone zones, no conglomerate, minor amounts of clay galls, and sizable ore bodies in a zone about 70 feet above the base of the Salt Wash. At Mesa IV, not shown on the cross-section, the Salt Wash is 100 feet thick, contains 60% sandstone, no coarse material, and important ore bodies in a zone about 40 feet above the base. The section is similar across the eastern mesas to Mesa I, except that ore remains about 60 feet above the base. At Mesa I, the total section is less than 100 feet thick and contains only 40 to 50% sandstone, six to ten mudstone zones, no coarse material and important ore bodies in a zone about 85 feet above the base.

An identical west to east facies change occurs on the southwest rim. From Mexican Cry to the east side of Step Mesa (fig. 6), the Salt Wash is exposed as a massive, cliff-forming, dominantly reddish sandstone which is separated at only a few places along the outcrop by slope-forming mudstone or interbedded mudstone and sandstone units. From the east side of Step to the west side of Two Prong, the Salt Wash is exposed as a series of sandstone ledges about 5 to 30 feet thick separated by about equal thicknesses of dirt- and brush-covered slopes formed on mudstone and interbedded units. Large quantities of ore occur in two zones about 40 feet and 100 feet above the base of the Salt Wash section. Along the west side of Two Prong, the Salt Wash is again exposed for perhaps 1,000 yards as a massive sandstone cliff. At the south edge of Two Prong, an equally abrupt facies change occurs: Bluff-type eolian sandstones rapidly rise in the section and intertongue with the lower 30 to 40 feet of the Salt Wash. The upper Salt Wash sandstones grade rapidly into red mudstone, leaving only 15 to 20 feet of recognizable Salt Wash.
Fine to medium grained sandstone with minor amount of mudstone seams and galls.
Granule conglomerate lenses.
Mudstone or interbedded mudstone, siltstone & sandstone.

FIG. 9

U.S. ATOMIC ENERGY COMMISSION
GRAND JUNCTION EXPLORATION BRANCH, DIVISION OF RAW MATERIALS
SALT WASH STRATIGRAPHY, MEXICAN CRY TO MESA II (LUCACHUAAI MTS., ARIZONA)


Gamma Log
Hence, three dominant facies of the Salt Wash, representing different depositional environments, exist on the Lukachukai mesas (fig. 5). On the western mesas, thick and continuous sandstones were deposited in a well-developed, fast water, channel system which was capable of eroding and transporting granule-size conglomerate and clay galls. The thick, channel sandstones grade laterally through an intermediate zone of lenticular sandstone and mudstone on the eastern mesas to a floodplain facies of mudstone and stray sandstone on the south and east side of the mountains. The change from fast water to quiet water sediments, from west to east, may be related to the apparent increase in CaCO₃ cement in sandstone cores on the eastern mesas (Lewis Roberts, personal communication). The dominant trend of deposition was north to northeast across the Lukachukai mesas, as shown on the facies map. The location and trend of the "lenticular sandstone and mudstone" facies conforms to the location and trend of ore on the mesas.

Within the "lenticular sandstone and mudstone facies," it is apparent that certain small areas of the ore-bearing sandstones are more lenticular than others. The lenticularity is marked where the outcrop has been stripped for mining, as shown by sections along the faces at Mines No. 12 and 24 on the southwest rim of Mesa I (fig. 10). Ore grade mineralization suitable for mining is in the thicker parts of the sandstone lenses, as shown by the location of mine portals. In general, the mudstone below the thick, ore grade sandstone is altered from red to green for about three feet vertically.

McKay (1951) noted a similar stratigraphic relationship in the Uravan and Gateway districts where carnocite deposits are restricted to areas of dominantly lenticular sandstone. He also demonstrated the importance of persistently altered mudstone underlying the sandstone. On the eastern Lukachukai mesas there is an increased thickness of gray mudstone near ore bodies, but quantitative measurements and maps were not made.

The ore zones do not follow a horizontal plane, as they might if deposition were controlled closely by a relatively level water table. From the southwest rim to the northeast rim, the base of the Salt Wash drops over 400 feet, but all the ore remains in an interval 40 to 90 feet above the base.

Subsurface Stratigraphy

Cross sections - Two cross-sections of core logs on Mesa IV₂ (pl. 3 and 4) and one of core logs on Mesa V (pl. 5) are presented to show the correlation of sedimentary units and other significant data.

Cross-section AB on Mesa IV₂ (pl. 3) shows a line of 12 holes through the center of three large ore bodies (see index map on same plate). The sandstone units BC, AD, and EF are of special interest because they contain ore at one or more places on the mesa, as shown on the index map. Notice that a maximum change in thickness of about 50% is seen in sandstone unit BC (i.e.,
DETAILED CROSS-SECTIONS OF LENTICULAR ORE-BEARING SANDSTONES EXPOSED ON MINE NO. 12 AND NO. 24, MESA I

FIG. 10
U.S. ATOMIC ENERGY COMMISSION
GRAND JUNCTION EXPLORATION BRANCH
DETAILED CROSS-SECTIONS ON MESA I
LUKAUCHUKAI MTS., APACHE CO., ARIZONA

INDEX MAP

EXPLANATION

Ore Grade Sandstone
Locatable
Mined-out Sandstone
Dispersed
Barren Sandstone
Red Mudstone
Green Mudstone
Mudstone Splits

Horizontal Scale 1" = 25'
Vertical Scale 1" = 10'

SCALE: AS SHOWN
DATE: MAR. 1952
TOPO. BY: CHECKED:
ACCOMPANIES:
GEOL. BY: R.D. Blum.
CORRECT:
DRAWN BY: R.D. Blum.
REVISED:
APPROVED:
SHEET:
FILE INDEX:

MINE # 12
MINE # 24
the thickness of BC in LU 676 is one half the thickness in LU 998). The
same unit shows the most rapid lateral color changes from red to tan or gray
and carries the thickest and highest grade ore bodies. Sandstone unit AD
does not vary as rapidly in thickness and the maximum thickness change shown
is 40%. No color change from tan or gray occurs, as shown on the cross-
section. Ore bodies in the unit are thin and generally of low grade; several
of the holes are weakly mineralized. Sandstone unit EF varies little in
thickness, the maximum change being 20%; the color stays red and no minerali-
ization is present in the holes.

Cross-section CD on Mesa IV½ (pl. 4) shows a line of 13 holes on the
margin of the main ore bodies, with the exception of LU 713 which cuts ore
in sandstone unit AD. All three sandstone units show variation in color,
and units AD and EF show more thickness variation than on the preceding cross-
section. Unit BC is partly tan and gray in LU 989 and 692 but contains no
ore; however, both holes are within 100 feet of LU 693 which is an ore hole
in the same unit. LU 713 cuts ore in tan or gray sandstone in unit AD;
the sandstone becomes red approximately 150 feet southward. Sandstone unit
EF changes from red to tan or gray a short distance north of LU 637 and
maintains that color a short distance beyond LU 951. Four of the five holes
within the strip of 100% tan or gray sand color, i.e., LU 637, 1083, 957,
and 955 are a maximum of 100 feet from an ore body in unit EF.

Cross-section AB on Mesa V (pl. 5) shows a line of 14 holes which crosses
the margins of four ore bodies. Sandstone unit XY, the ore carrier, has
a maximum thickness variation along the line of cross-section of 30%. Color
variation from red to tan or gray in the vicinity of ore is not as clear-cut
on this cross-section as on the two previous sections, although there is
obviously some increase in tan or gray color near ore. Other logs on Mesa V
show a greater degree of change, but the variation on Mesa V was not so pro-
nounced as on Mesa IV½.

Sandstone thickness. The importance of sandstone thickness changes,
deduced from outcrop information and suggested by the cross-section, indicated
that contour maps of sandstone thickness might prove useful. Accordingly,
isolith maps of the total sandstone thickness (exclusive of interbedded mud-
stone) in units AD and BC on Mesa IV½ (pl. 6) and unit XY on Mesa V (pl. 7)
were constructed.

Figs. 1 and 2, Plate 6, show isolith contours of total sandstone
thickness of sandstone units AD and BC; areas of sandstone thickness less
than 10 feet are marked by ruled lines. Holes in which the sandstone units
could not be accurately measured are not shown, unless the holes are minerali-
zed. The isolith map of sandstone unit AD shows a large sand area in the
center of the mesa ranging from 10 to 20 feet thick. All of the ore occurs
in sandstone ranging in thickness from 11 to 18 feet. Outlines of the ore
bodies do not closely parallel the isolith contour lines. The trend of
deposition cannot be determined with certainty in this small area, but it ap-
ppears that one large sand bar, and a smaller one in the southwest corner of
the mesa, have a north or northeast alignment.
The isolith map of sandstone unit BC shows more irregularity, hence more lenticularity than sandstone unit AD. The ore bodies are considerably larger and higher grade. The map shows an irregular sandstone area in the center of the mesa, consisting roughly of two main sandbars which range from 10 to 20 feet in thickness. Most of the ore is in sandstone ranging from 10 to 20 feet in thickness. The outline of the northern ore body closely parallels the isolith contours of the sand lens. The easternmost, oblong-shaped ore body also roughly parallels the contours of the sand lens. The trend of deposition in this area cannot be determined, although some of the contours maintain a northward lineation.

The isolith map of sandstone unit XY on Mesa V (fig. 1, pl. 7) demonstrates ore accumulation conditions similar to Mesa IVβ. The ore bodies are about equal in value to those in unit BC. The map shows three sand bars 30 to 50 feet thick in northwest alignment across the central part of the mesa. The sand bars are bounded on the northeast and southwest by narrow belts of thin, usually shaly sandstone less than 30 feet thick and marked on the map by ruled lines. Two other sand bars are shown on the west and south-central parts of the map. Most of the ore occurs in sandstone ranging in thickness from 35 to 50 feet. The main ore bodies are clearly aligned along the main northwest channel trend. The outline of the large southernmost ore body fits closely the isolith contour lines of the southern sand bar; the large northern ore body fits the general trend of isolith contour lines of the northern sand bar. The trend of deposition outlined in this area fits almost exactly a structure or channel contour map drawn on the base of the XY sandstone zone and corrected for structural dip. The channel contour map is suggested as an alternative method of determining stratigraphic trends. However, localization of ore bodies in sand bars within the main channel is not shown so clearly as on the isolith maps.

Conclusions from the isolith maps can be illustrated partially by graphs. Lenticularity of the three sandstone units is shown on Figure 11 by plotting the sandstone thickness versus the number of drill holes in which each thickness occurred; the general distribution of ore, according to thickness, is shown by a bar across the graph.

The graph of unit AD is a high peaked, relatively smooth curve of thicknesses ranging from 5 to 22 feet; 70% of the holes cut 12 to 17 feet of sandstone, indicating that lenticularity is not pronounced. All of the ore occurs in 11 to 18 feet of sandstone. The graph of unit BC is an irregular, relatively flatter curve with a similar range in thickness from 4 to 22 feet; but only 40% of the holes have 12 to 17 feet of sandstone, indicating that there is a wider range of thicknesses, hence more lenticularity. Most of the ore occurs in 10 to 20 feet of sandstone. The graph of unit XY compares in form with that of unit BC, although the thickness range from 20 to 50 feet indicates less maximum percentage change in thickness. Most of the ore occurs in 35 to 50 feet of sandstone.
All Ore in This Thickness Range

Most Ore Found in This Thickness Range

FIG. II
VARIATION IN SAND THICKNESS OF ORE ZONES ON MESAS IV\textsubscript{1/2} & V
LUKACHUKAI MTNS.,
In summary, ore occurs in lenticular sandstones and is concentrated primarily in the central to median parts of the lenses. Further, the general trend and localization of ore bodies on a mesa conforms closely to the sedimentation pattern, and the outline of large ore bodies follows rather closely the contour outline of the sand lenses.

**Color maps.** The subsurface cross-sections suggest the significance of color as a guide to ore. Previous cross-sections by Lowell (1951) show similar conditions. Isopercenage maps of the relative thickness of tan or gray sandstone in units AD and BC on Mesa IV (pl. 6) and unit XY on Mesa V (pl. 7) were constructed.

Figures 3 and 4, Plate 6, show isopercenage contours of the tan or gray sand percentage of sandstone units AD and BC. Each percentage figure was rounded off to the nearest 25% because of the large margin of error incident to choosing the exact position of color breaks. Holes in which the tan or gray sand percentage could not be measured are not shown, unless they are mineralized.

The color map of unit BC shows a remarkable correlation of ore bodies and mineralized holes with the central parts of high percentage tan or gray sand areas. Zero to 25% tan or gray sand areas are marked by ruled lines. In only one locality is there a slight overlap of the ore body into the ruled area. The outline of each ore body also conforms closely to the outline of each "color pod." Each of the four main color pods is located in a part of the two main sand bars (see fig. 2, pl. 6) with a certain amount of overlap into the areas of thinner sandstone. The color pods are distinctly separated units and represent a condition of rapid lateral change in color.

The color map of unit AD shows a more simple picture of color distribution, just as the isolith map of unit AD was more regular than that of unit BC. Unit AD is 100% tan or gray over most of the central part of the mesa. The ore bodies are small, whereas a considerably larger percentage of holes are mineralized than in unit BC. A significant feature of the map is that each ore body, including single ore holes, is in an area of rapid lateral color change. Two ore bodies and three ore holes are located on the western and eastern flanks of the north-trending color zone. Ore bodies within the main color zone lie on the flanks of local concentrations of red color. The tan or gray color zone fits the general sandstone isolith pattern (fig. 1, pl. 6) and the local pods of red color lie in local areas of sandstone thinning. Overall, there is less lateral variation in color than in unit BC.

The color map of sandstone unit XY on Mesa V (fig. 2, pl. 7) was drawn in the same manner as the maps of BC and AD, except that percentage figures were rounded off only to the nearest 5%, and holes without percentage measurements were left on the map. The contour interval is 25%, as on the preceding color maps.
The tan or gray color pods in unit XY are intermediate in size and regularity between those in AD and BC. Each ore body and five of the seven single ore holes lie on the margins of the color pods, in the areas of rapid lateral color change. Most of the smaller ore bodies lap farther into the 0 to 25% color area than was typical on the other maps. The major areas of tan or gray color fit generally with the thick sandstone areas of the isolith map. The general distribution of ore is shown on the maps to fall mainly within the zone of 25% to 100% tan or gray sandstone.

Conclusions from the color maps can be illustrated partially by graphs. The degree of lateral color variation of the three sandstone units is shown in Figure 12 by plotting the different percentages of tan or gray sandstone encountered in drill holes versus the number of holes in which each percentage figure occurred.

The graph of unit AD shows that a very high proportion of the holes contain 100% tan or gray sandstone, indicating a small amount of color variation. The graph of unit BC is much different in form and shows that tan or gray sandstone and red sandstone are about evenly distributed in total amount, indicating a condition of much more rapid color variation. The graph of unit XY is similar to that of BC, except that there is even less tan or gray color, although the maps show that color variation in XY is not quite so rapid as in BC.

A comparison of the grade of mineralization in units AD and BC is interesting. There are 14 ore grade holes and 41 mineralized holes in unit AD, making a total of 55 holes with mineralization. There are 29 ore grade holes and 30 mineralized holes in unit BC, making a total of 59 holes with mineralization. It seems logical to conclude that approximately the same amount of uranium occurs in unit AD as in BC, but is not so thoroughly concentrated in AD because of less efficient trap conditions.

In summary, ore is associated with "pods" of tan or gray sandstone, or is located on the flanks of larger zones of tan or gray sandstone. The tan or gray color areas of a particular sandstone unit generally conform to the areas of thicker sand and follow the main trends of sedimentation. Lateral changes in sandstone color appear to be of key importance in recognizing favorable areas for ore-grade mineralization.

Hypothesis of stratigraphic control of ore deposits - The north to northeast trend of ore deposits on the eastern Lukachukai mesas conforms to a similarly trending facies belt of "lenticular sandstone and mudstone" which is bounded on the northwest by thick, continuous channel sandstone and on the southeast by floodplain mudstone and "stray" sandstone. Ore concentration within the intermediate facies is a result of there being sufficient sandstone in the section to carry ore solutions, and sufficient and properly distributed mudstone to canalize, or concentrate, solution flow along certain sandstone beds. The large ore deposits are restricted to sandstone lenses which show rapid lateral variation in thickness, amounting to maximum thickness
FIG. 12
VARIATION IN SAND COLOR OF ORE ZONES ON MESAS IV 1/2 & V
LUKACHUKAI MTNS., ARIZONA
changes of approximately 50% or more. Smaller ore deposits are present in less lenticular sandstones. It is presumed that large areas within the main ore trend, e.g., Mesa II, may not contain sandstones with the necessary thickness variation to have trapped mineralized solutions in economic quantities.

The changes in sandstone thickness associated with ore concentrations probably do not represent complete permeability blocks because no complete sandstone pinch-outs have been observed. Solutions could not move laterally between sandstone lenses completely enclosed in mudstone. The changes in sandstone thickness do represent pronounced changes in transmissibility. The term "transmissibility" is defined as the ability of a stratum to transmit fluids and is a measure of cross sectional area x permeability. 

Transmissibility decreases rapidly in the vicinity of decreasing sandstone thickness because of the decreased cross-sectional area of the bed and because the thinner sandstones tend to be shaly and consequently less permeable. The "stagnation" or slowing down of mineral-bearing solutions is apparently caused by a pronounced decrease in transmissibility of the sandstone conduit. Hypothetically, solutions would first begin to precipitate uranium along a zone of decreased transmissibility in the median part of the sand lens. The locus of precipitation would tend to move inward toward the center of the lens, ultimately "filling" the permeable bed.

In the vicinity of ore deposits, color of the ore-bearing sandstone commonly changes from red to tan or gray. Color maps show that areas of tan or gray sandstone follow the general sedimentation pattern and are partially restricted to the thicker parts of the sandstone beds. The sandstones which vary laterally in this way from red to tan or gray were probably red before introduction of the mineralizing solutions which bleached part of the color. (Sandstone beds which are tan or gray over large areas, with no color variations, were probably deposited as tan or gray sandstone.) The fact that bleached zones follow the most logical permeability paths suggests that the zones of tan or gray sandstone represent zones of high transmissibility. Hence, areas of color change represent the trap areas of transmissibility change.

The subsurface maps show that the dominant trends of ore on particular mesas are related to stratigraphic trends. In addition, the outlines of large ore bodies follow fairly closely the contour outlines of sand bars. The smaller ore bodies do not follow the contour outlines of the present isolith maps as a result, possibly, of lack of detailed contour control. Reorientation of ore bodies across depositional trends and parallel to structure has not taken place.

Application of stratigraphic hypothesis to prospecting - Within a mineralized region, the most favorable areas of Salt Wash for ore-grade con-

1/ The term "transmissibility" is defined as the ability of a stratum to transmit fluids and is a measure of cross sectional area x permeability.

- 31 -
Centrations of uranium and vanadium are those with approximately 50% of interbedded mudstone. The Salt Wash outcrop in such areas is characteristically broken, with ledges of sandstone separated by dirt- and brush-covered slopes.

Lenticularity of sandstone beds is difficult to determine from partially covered outcrops without detailed examination. However, most of the ore bearing sandstones contain mineralization at one or more exposures, hence, favorable strata need not be determined by thickness measurements.

Sandstone beds which change color from red to tan or gray along the outcrop should be considered good possibilities whether or not mineralization is found on the outcrop.

The initiation of drilling on a mesa should be preceded by a careful outcrop study to determine as much sandstone thickness and color information as possible. Areas of thick sandstone and tan or gray color should be projected into the mesa and the trends extended by drilling.

Subsurface maps of sandstone thickness and color should be constructed during drilling and used in combination to predict favorable areas. The large ore deposits occur in zones of relatively thick sandstone which change laterally in color. It is probable that maps of green mud distribution would also be useful. In areas where drilling has been completed, the core logs should be restudied to determine if any favorable areas were missed. Several good prospects are shown on the ‘Mesas IV$^1_2$ and V maps and will be recommended for investigative drilling at a later date.

Accurate subsurface maps can be constructed about midway through a closely spaced drilling project after a sufficient number of holes are drilled to establish correlation and provide adequate contour control. Correlation holes on the Lukachukai mesas must be about 250 feet apart, but drilling a complete 250-foot grid is unnecessary. As shown on the Mesa V map, widely spaced holes can be “tied” to two or three transecting correlation “lines.” The closely spaced holes on correlation lines are necessary to establish the stratigraphic units and facies changes which are present on the mesa.

The favorable thicknesses of ore-bearing sandstone in one district cannot be used to indicate favorability in another district. Thus, whereas 40 feet or more of sandstone thickness is favorable in the Uravan district (Blackman, 1951), it is relatively unfavorable on Mesa IV$^1_2$. Changes in sandstone thickness are the guide to favorability. In the same way, changes in color from tan or gray to red rather than a persistent tan or gray color delineate favorable areas.
ORIGIN AND DEPOSITION OF URANIUM-VANADIUM ORES
IN THE
LUKACHUKAI MOUNTAINS AREA

Geologic information from the Lukachukai Mountains area does not indicate clearly the syngenetic origin of uranium and vanadium proposed by Fischer (1948) and Bain (1951), nor the hydrothermal origin proposed by Dodd (1951), Reinhardt (1951), and Shoemaker (1951). However, the facts are not opposed to the general concept of deposition associated with hydrothermal origin.

At this time, Shoemaker's (1951) detailed study of the Uravan or La Sal Mineral Belt is the most conclusive and well substantiated picture yet presented of the origin of uranium mineralization in a large district. He has observed carnitite-type mineralization in fault gouge and in numerous formations other than Salt Wash where the formations are adjacent to faults. Minerals commonly associated with the carnitite are hydrothermal types. The principal carnitite mines are located in a discontinuous "belt" around the south, east, and north sides of the La Sal laccolith. Concentrations of mineralization occur on or adjacent to the northwest-trending salt anticlines which are cut by northwest-trending normal faults. Shoemaker suggests that hydrothermal solutions from an underlying magma moved upward along faults and into the adjacent sedimentary rocks. Highly permeable stream sediments such as the Salt Wash provided strata through which mineralized solutions in ground water could move laterally long distances, given sufficient hydrostatic pressure.

Reinhardt (1951) believes that mineralized solutions in the Salt Wash moved laterally from the laccolith and were precipitated in an imperfect "double ring" around the mountains with concentrations across the structurally high anticlines because of water table conditions. Almost no contact metamorphism is found at the intrusive-sedimentary contact and Shoemaker argues that the relatively "dry" injection could not have provided, by itself, a sufficiently large quantity of hydrothermal solutions to account for the "La Sal Mineral Belt."

The Carrizo Mountain laccolith is 10 miles north of the Lukachukai mesas. The Salt Wash sandstone is mineralized around the flank of the laccolith and on mesas to the west and south, including the Lukachukai mesas. Twelve miles southeast of Cove, ore grade mineralization occurs in the Recapture sandstone in the Sanastee area.

Almost no contact metamorphism has taken place around the Carrizo laccolith and flanking sediments are sharply tilted, suggesting that the intrusive was low in volatiles and viscous. Hydrothermal solutions
in sufficient quantity to mineralize the large surrounding area were probably not contained in the volume and type of rock represented by the presently exposed laccolith. However, a very large subsurface magma body apparently underlaid the entire region and fed the many dikes, plugs, sills, and flows, as well as the laccolith. A magma body of such immense size could probably account for almost any degree of mineralization.

It is difficult to determine whether the mines around the Carrizo laccolith represent a "halo" of mineralization or only a circular exposure of mineralized rock. The author is inclined to discount the possibility of lateral movement of solutions from the laccolith, but a "halo" effect could still exist as a reflection of upward movement of solutions along subsurface fractures concentric to, and caused by, the laccolithic intrusion. Such fracture or joint patterns would be discontinuous and highly variable in their capacity to transmit hydrothermal solutions. As a result, certain areas of Salt Wash would receive stronger "injections" of mineralization into the ground water contained in the sedimentary rocks. Precipitation of carnotite would occur in the nearest ground water traps.

Certain facts and inferences suggest the possibility of more than one main source area of mineralization. Examination of the geologic map (pl. 1) indicates a concentration of ore bodies on or adjacent to deformed strata, as in the La Sal district. Again, this fact may be related to outcrop pattern, but large areas of flat Salt Wash do not seem to have the ore concentrations that are found adjacent to the Lukachukai monocline or the Rattlesnake monocline northwest of the Carrizo Mountains and in the tilted strata around the mountains. The ore in Recapture sandstones near Sanastee is on the Defiance monocline. An example farther afield is the Monument No. 2 mine close to the Comb Ridge monocline. Williams (1936) has shown the relationship of igneous intrusions in the Monument Valley area to a joint pattern developed along the Comb Ridge monocline. The author has suggested the possibility that most of the Plateau monoclines are underlain by faults in the basement rock, and the possibility that intrusions and extrusions in the Chuska Mountains are related to a zone of subsurface weakness or faulting along the Defiance monocline. Concentrations of mineralization adjacent to monoclines, if that observation is correct, may well be related to faults at depth with related zones of weakness or fracturing in the rock involved in the flexures. Such zones, as fracture patterns around laccoliths, would be discontinuous and highly variable in their capacity to transmit hydrothermal solutions.

The Sanastee area is 25 miles south of the Carrizo laccolith (pl. 1). The writer's interpretation of Tertiary history and erosion surfaces suggests that mineralizing solutions originating in or near the Carrizo laccolith of Pliocene (?) age would have to pass Cove on the east side in order to reach the Sanastee area via Recapture beds. The Tertiary unconformity, which is probably pre-laccolith in age, cuts out Recapture rocks for a long distance down the west side of the Chuska Mountains. Ground water in Recapture rocks which moved eastward from the Carrizo Mountains would travel downdip toward the San Juan Basin. To reach
the Sanastee area, that ground water would have to turn at right angles to the normal course and move laterally almost 25 miles along the strike. Such movement is difficult to imagine, hence, a nearer source of mineralized solutions is logical. A subsurface fault underlying the Defiance monocline could provide a pathway for hydrothermal solutions.

The above inferences suggest that ore on the Lukachukai mesas may be related to a subsurface fault below the Lukachukai monocline instead of to a fracture zone around the Carrizo laccolith, or to lateral migration from the laccolith itself.

Deposition of carnotite by ground waters at some stage in the mineralizing process has been proposed by all students of the problem, whether proponents of syngenetic or hydrothermal origin theories. The author agrees that all indications from the shape and appearance of ore bodies point to ground water deposition. Information from the Lukachukai mesas suggests that the ground water flow only conforms to structure by flowing downdip. Otherwise, the water follows the old sedimentation trends of sandstone lenses and is canalized by mudstone beds and trapped by changes in sandstone transmissibility. Maximum transmissibility changes are caused by sandstone lenticularity and permeability differences, hence, the transmissibility is directly related to original depositional patterns and original, or later, cementation. On the Lukachukai mesas, optimum structural trap conditions existed in the Lukachukai syncline, especially in the very flat part of the syncline across Mesas V, VI, VII, and Mexican Cry. However, no ore was deposited in the syncline.

Leaching and reprecipitation of carnotite from the stratigraphic traps is possible on a small scale, as shown by surface "paint" considerably out of radioactive equilibrium. However, large-scale relocation and reorientation of ore bodies is improbable if the ore is considered to have originated from Tertiary hydrothermal solutions. At the time of mineralization, structural and stratigraphic conditions, as well as general direction of ground water flow, were the same as today. Because the major geologic conditions have not changed, it is improbable that the ore traps have been altered appreciably in trap orientation or trap efficiency.

SUMMARY

A sequence of events and conditions in the geologic history of the Lukachukai Mountains area caused the present distribution and localization of carnotite ore. Those events have been interpreted, with varying degrees of accuracy, from the information available. The interpretations are presented to partially summarize this paper and to show the framework of ideas which contributed to the discussion on preceding pages of carnotite origin and deposition in this area. Some interpretations of the geologic history are dependent on other interpretations. The author has attempted to rate the accuracy of each interpretation to indicate the strength of each "link" in the "chain" of events.
1. Correct: Almost 13,000 feet of Paleozoic and Mesozoic sediments were deposited in the area. The stratigraphic column from Chinle to Morrison is now exposed on the Lukachukai Mountains.

2. Correct: Major structures of the area were formed in late Cretaceous or early Eocene by Laramide orogeny. The Lukachukai monocline is pre-Tohatchi and probably Laramide in age.

3. Correct: Laramide structures were truncated by Tertiary erosion previous to deposition of the overlying Tohatchi and Chuska formations.

4. Correct: Intrusion of basaltic-type rock occurred after deposition of the Tohatchi and Chuska, presumably in Pliocene.

5. Probable: Intrusion of the diorite porphyry of the Carrizo laccolith occurred at approximately the same time as intrusion of the basalt.

6. Possible: Hydrothermal mineralizing solutions entered ground water in the Salt Wash sandstone during the period of igneous intrusion. The following interpretations and ratings are related to the hypothesis of hydrothermal origin.

7. Possible: Mineralized solutions moved upward along zones of subsurface fracturing and faulting around the Carrizo laccolith and under the monoclines.

8. Correct: Mineralized solutions entered ground water which moved primarily in the highly permeable Salt Wash sandstones.

9. Correct: Present day structure existed at the time of mineralization and exerted general hydrostatic control on ground water movements.

10. Probable: The Tertiary erosion surface exists today as it did at the time of mineralization. Ground water in Salt Wash and other strata at the time of mineralization could not move through areas where the rocks has been removed by pre-Tohatchi erosion.

11. Correct: Mineralized ground water was canalized along sandstone beds between layers of impermeable mudstone. Concentrations of ore deposits occur in areas of Salt Wash containing about 50% interbedded mudstone.

12. Correct: Large ore bodies occur in stratigraphic traps where ground water "stagnated" as a result of decreases in transmissibility caused by sandstone thickness and permeability changes.

13. Correct: Solutions moving as ground water "bleached" red sandstone to tan or gray. Thickness and color maps show that the solutions were restricted to the central parts of sandstone lenses. Areas of color
change in the central or median parts of the lenses indicate areas of transmissibility change which represent trap conditions.

14. Correct: Mass relocation and reorientation of ore bodies along structural trends has not taken place. No changes in geologic conditions have occurred since the time of mineralization which would cause such alterations in trap efficiency or orientation.

RECOMMENDATIONS

In mineralized areas, stratigraphic studies of Salt Wash facies changes are valuable methods for locating favorable ore-bearing rock.

Detailed outcrop studies of sandstone thickness, color changes, and other ore criteria should precede and be coordinated with all drilling programs.

Detailed subsurface geology, in conjunction with outcrop information, can enlarge target areas and guide drilling. Old drilling areas should be re-examined for possible extensions and to learn more about the geologic criteria of ore-bearing rock.

The correlation of mineralized areas with nearby monoclinal flexures, as well as laccoliths, should be studied regionally to determine if the trend of large structures can be used as a general guide to new areas of mineralization, either exposed or covered.

If the Salt Wash is ore-bearing because it is composed of lenticular, fluvialite sandstones, then vast areas of the Mesa Verde and Dakota formations should be prospected.
APPENDIX A

METHOD OF STRUCTURE MAPPING

Stafford (1951) compiled a structure map of Mesas I, II, III, and IV from work of his own and other USAEC personnel. J. W. King's field party compiled accurate structure maps on Mesas V, VI, VII, and Mexican Cry. Mesas V and VI were mapped by plane table, Mesa VII by combination plane table and altimeter, and Mexican Cry by altimeter. Control points were 200 to more than 1,000 feet apart.

The author, assisted by R. D. Blum, remapped Mesas I through IV because parts of the first map appeared to be inaccurate. The method used in remapping was unconventional but reasonably accurate and very fast. Other field parties may find the method useful for mapping low dip structure in canyon-mesa topography. Beginning near the northwest end of Mesa II, by control point 57, a plane table and alidade were set up about 40 feet below the top of the Bluff. The alidade was leveled and swung in an arc until the middle hair cut the Bluff-Salt Wash contact near the tip of Mesa IV (contact point number 58). The point was located on the USGS topographic map, scale 1" = 500', which was plotted from aerial photos. The alidade was moved up the hill about 15 feet (exact distance was determined by hand leveling), a level line sighted to point number 48 on the east side of Mesa IV, and the point marked on the map. Several more points were shot along the east edge of Mesas IV and III as the alidade was gradually moved up the hill. Vertical distance from the highest alidade station to the top of the hill was hand-leveled and a flag left for a marker. Elevation of the flag was later determined by plane table traverse to the nearest reliable elevation marker. Elevation of each alidade station on the hill was determined by subtracting the hand level distances from the flag elevation. The elevation of the contact point shot on a level line from each alidade station was, of course, equal to elevation of the station. All rim control points shown on the map from Mesa IV to Mesa I were obtained in this manner. The tips of Mesas IV and III were shot in twice from different locations to determine accuracy of the work. Control points 27 and 58 on the tip of Mesa IV differ by three feet; control points 45 and 51 on the tip of Mesa III differ by five feet.

Much of the drill core is still preserved in storage areas on the mesas, hence it was possible to check the lithologic "picks" of the top of the Bluff and use the holes for control points. The Bluff elevation was changed in the following logs: JU 22, 42, 71 (Mesa I); 105, 109 (Mesa II); 365, 366 (Mesa IV). Most of the holes drilled to Bluff were resurveyed to insure accurate structural elevations. On Mesa I, drill hole elevations were taken from work by Anaconda engineers who resurveyed that mesa for a study of probable ore reserves.
APPENDIX B

SURVEY CONTROL

by

R. D. Blum

The existing survey control in the Lukachukai Mountains area has been done by the USGS, the USAEC, and the Navajo Uranium Mining Company. The work done by the USGS is first or second order triangulation consisting of three triangulation stations on the mountains, a line of levels from Red Rock to Cove Mesa, and another line of levels from Lukachukai Trading Post westerly. Both level lines have permanent Bench Marks every few miles beside the road.

The triangulation station data are as follows:

Luka
- Lat. 36° 30' 13.417"n
- Long. 109° 11' 49.425"
- V. A. Elevation 9,413. feet.

Center
- Lat. 36° 30' 11.620"n
- Long. 109° 14' 30.480"
- V. A. Elevation 8,304. feet

View Point
- Lat. 36° 31' 54.910"
- Long. 109° 09' 47.930"
- V. A. Elevation 9,114. feet

The station View Point is located on the igneous sill east of Cove School and is marked by a crossed triangulation flag. The station Luka is located south of View Point on a hill; it is marked the same as View Point. The station Center is located directly south of Mesa II on one of the highest points in the surrounding mountains. It is marked by an ordinary flag and is shown on the USGS topographic maps thusly: x8808.

The work done by the USAEC and the private companies is of fifth order accuracy. Most of the surveying done by the Navajo Uranium Mining Company has been in their underground workings on Mesa I. Anaconda engineers made a transit survey of most of the drill holes on Mesa I for Navajo Uranium Mining Company. However, their elevation datum is 245 feet below the datum used by the USGS.

Much of the data from the work done by the USAEC were not preserved. The work was done by plane table triangulation and intersection, the initial control coming from the USGS triangulation. These stations are located on Mesar IV, V, and VI, and are shown on Pl. II. The stations on Mesa IV are:
Tip of IV  Elevation 7297.0  
Jeep  Elevation 7392.5  
Mine  Elevation 7398.0

The station Tip of IV is on the north point of Mesa IV on the Salt Wash-Bluff contact and is marked by a survey stake driven into the ground and an ordinary white flag. The station Jeep is located at the north end of the road that runs the length of Mesa IV and is marked by a survey stake. The station Mine is located at the end of a road that goes down to a stripped face on the west side of the Mesa. This is the last road that turns off to the left when traveling from south to north on the main road of Mesa IV.

The stations on Mesa V are:

<table>
<thead>
<tr>
<th>Station</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7505</td>
<td>7505.0</td>
</tr>
<tr>
<td>Tree Point</td>
<td>7757.7</td>
</tr>
</tbody>
</table>

The station 7505 is located on the highest point on the eastern half of Mesa V and is marked by an ordinary flag on a 14-foot pole. The station Tree Point is located approximately two-thirds the way up the only hill on the west half of the mesa on a line between 7505 and the top of the hill. It is marked by a red flag on a 13-foot pole and farther up the hill is a white flag in a tree.

The stations on Mesa VI are:

<table>
<thead>
<tr>
<th>Station</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinion</td>
<td>7313.7</td>
</tr>
<tr>
<td>Piedra</td>
<td>7698.6</td>
</tr>
</tbody>
</table>

The station Pinion is located on the highest point on the east end of the mesa and is marked by a flag on an 8-foot pole. The station Piedra is located approximately one-third of the length of the mesa from the west end on the east edge of a topographic bench. The stations on Mesa VI are several hundred yards from the nearest road and are accessible only by walking about 1 mile of brushy, rough terrain.

These stations on the three mesas have been located by the USACE with the accuracy required for structural mapping and diamond drill location, hence they are not of such permanence to be useful beyond a probable period of 10 years from the present.
APPENDIX C
ORE RESERVES

<table>
<thead>
<tr>
<th>Mesa</th>
<th>Total Tons (Drilling and Mining)</th>
<th>Av. Grade U₃O₈</th>
<th>Value factor Tons x grade 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>59,000</td>
<td>.36</td>
<td>21</td>
</tr>
<tr>
<td>IV½</td>
<td>37,000</td>
<td>.30</td>
<td>11</td>
</tr>
<tr>
<td>V</td>
<td>24,000</td>
<td>.18</td>
<td>5</td>
</tr>
</tbody>
</table>

On Mesa I, the original calculations of indicated and inferred ore (Stafford, 1951) equaled 76,400 tons; as shown on Figure 7, the outlines of ore bodies were determined on the assumption of a northwest trend which is believed by the author to be false. Furthermore, the two large ore bodies adjacent to the southwest rim of the mesa and being developed by mining were not discovered or outlined by drilling. Tonnage estimates from those two ore bodies cannot be included in indicated and inferred ore discovered by AEC drilling. The author suggests that a maximum of 45,000 tons of indicated and inferred ore averaging .38% U₃O₈ and .74% V₂O₅ can be calculated from Mesa I drilling results. In addition, the Navajo Uranium Company, formerly F. A. Sitton, Inc., has shipped to date from Mesa I about 14,000 tons of ore averaging .30% U₃O₈ and 1.26% V₂O₅ (Crew and Lowell, in preparation). The Climax Uranium Company has shipped to date from Mesa IV½ about 2,200 tons of ore averaging .24% U₃O₈ and .94% V₂O₅.

AEC drilling on Mesa V discovered about 24,000 tons of indicated and inferred ore averaging .19% U₃O₈ and 1.31% V₂O₅ (Crew and Lowell, in preparation). The Navajo Uranium Company has shipped to date from Mesa V a negligible amount of ore.
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