THE URANIUM DEPOSITS OF NORTHEASTERN ARIZONA
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Introduction

In northeastern Arizona and adjacent areas in Utah and New Mexico significant amounts of uranium have been produced from deposits in the Chinle and Morrison Formations. Minor deposits occur in the Bidahochi, Kayenta, Moenkopi, Navajo, and Toreva formations. A total of 14,017,000 pounds of U3O8 has been produced to date. Although this is only three percent of the total U.S. production, the production from the Chinle here represents approximately 13 percent of the total production that has been derived from the Chinle. Production from the Morrison Formation in northeastern Arizona, and the adjacent area in New Mexico, is restricted to the Salt Wash Member and represents approximately 5 percent of the total Salt Wash production.

All of the mines, with the exception of those in the Winslow-Holbrook-St. John's area and those near Black Point in the Cameron area, are on the Navajo Indian Reservation. On the Reservation, mining permits and leases are granted by the Navajo Tribal Council at Window Rock, Arizona. Uranium mining has provided the Tribe with significant income from royalties and rentals, as well as employment for the members of the Tribe. At the present time, the area is inactive and there are no leases in effect on the Reservation in northeastern Arizona and adjacent areas.

Deposits in the Chinle Formation

Exposures of the Chinle Formation in northeastern Arizona occur in Monument Valley on the Monument uplift, along the west and south flanks of the Black Mesa Basin, and on the Defiance uplift on the east side of the Basin. In Monument Valley, the formation is composed of five members which, in ascending order, are: the Shinarump, Monitor Butte, Petrified Forest, Owl Rock, and Church Rock. Uranium deposits in northeastern Arizona occur in the Shinarump and Petrified Forest Members and in an equivalent of the Monitor Butte Member.

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Shinarump Member - The Shinarump consists of fluvial sediments which were deposited in stream channels and flood plains. These sediments are composed of lenticular beds of sandstone, conglomerate, siltstone and mudstone; they contain abundant fragments of carbonized wood and minor amounts of silicified wood. This resistant unit generally forms a broad bench and in Monument Valley it caps mesas and buttes. The sandstone is commonly light tan to light gray in color, cross-stratified, medium- to coarse-grained and usually conglomeratic at the base. The conglomerate is composed of well-rounded to sub-angular pebbles and cobbles of quartzite, quartz, chert with some limestone, sandstone, siltstone and mudstone. Calcite is the most common cementing material in the sandstone and conglomerate. Mudstone in the member consists of lenses varying in color from pale red to greenish gray. The thickness of the member varies greatly as it fills valleys and scours eroded into the underlying rocks. In Monument Valley, the thickness of the Shinarump ranges from approximately 10 feet to nearly 250 feet.

The recognition of Shinarump channels and channel patterns is important, because all of the significant uranium deposits in Monument Valley are in these channels.

Monitor Butte Member - The Monitor Butte intertongues with the Shinarump and consists of red to greenish-gray mudstone and siltstone with some light brown to gray, very fine- to coarse-grained sandstone. The member ranges in thickness from 50 to 200 feet. Lateral equivalents of the Monitor Butte in northeastern Arizona include the sandstone and mudstone member, the lower red member, and the Mesa Redondo Member (Stewart and others, 1972). Minor uranium deposits in the Cameron area occur in the sandstone and mudstone member.

Petrified Forest Member - Overlying and gradational with the Monitor Butte and its correlatives is the Petrified Forest Member. The lower part of the member is comprised of blue, gray, and white mudstone and tuffaceous siltstone. Lenticular sandstones are present in the lower part of the member in the Cameron area. The upper part of the member consists of grayish red, pale reddish-brown, and pale reddish-purple mudstone, siltstone, and sandy siltstone. In the eastern part of the Black Mesa Basin the Sonsela Sandstone Bed separates the two parts of the member. The Petrified Forest Member ranges in thickness from 500 to 1,200 feet in northeastern Arizona.
Owl Rock Member - Overlying and intertonguing with the Petrified Forest Member is the Owl Rock Member. It is comprised of pale blue and grayish-pink limestone in beds up to 20 feet thick. The limestone contains abundant chert nodules, mudstone pellets, and lenses of limestone pellet conglomerate. Interbedded with the limestone is pink and reddish-orange calcareous siltstone. The Owl Rock ranges in thickness from 130 to 300 feet.

Church Rock Member - In Monument Valley, the Church Rock Member overlies the Owl Rock. It consists of 150 to 300 feet of reddish-orange to reddish-brown siltstone and sandstone. Strata lithologically similar to the Church Rock Member of the Chinle are included in the Rock Point Member of the Wingate Sandstone elsewhere in northeastern Arizona (Stewart and others, 1972).

Monument Valley area
The Monument Valley area is in the southern portion of the Monument upwarp where erosion has dissected a high tableland. The name of the mining area is derived from Monument Valley where erosion of massive eolian sandstones has produced spectacular monolithic landforms. Here, the Shinarump Member of the Chinle Formation crops out around the perimeter of the uplift and also caps mesas within Monument Valley (fig. 1).

Gregory (1917, p. 148) during his reconnaissance of the Navajo country noted a yellow uranium mineral, probably carnotite, in the Shinarump of Monument Valley. A brightly-colored outcrop of uranium-vanadium minerals, which was to become the Monument No. 2 mine, was brought to the attention of the Vanadium Corporation of America, who leased the area in August 1942. This discovery resulted in additional prospecting which found other exposures in the central part of the area. Although some vanadium ore was produced during 1942-1944, significant production did not begin until 1948 when uranium became important. In the late 1940s and early 1950s, many deposits, small to medium in size were discovered in paleochannel exposures at rim outcrops. In 1955 and 1956, a cluster of important deposits including the Moonlight mine was discovered in buried channels at moderate depths in the central portion of Monument Valley. Production in Monument Valley reached a peak in 1955, when 14 mines were operating, and gradually declined until the last shipment was recorded in late 1969. During this period, a total of 1,362,000 tons averaging 0.32 percent U₃O₈ and containing 8,730,000 pounds U₃O₈ were produced from 53 properties. Vanadium which was recovered from 97 percent of this production averaged 0.94 percent V₂O₅ and aggregated 24,780,000 pounds V₂O₅. Most of the ore that was produced from the Monument No. 2 mine was beneficiated in an upgrader located at the mine site.
Shallow deposits at or near an outcrop were mined by adit or open pit, depending on the size of the deposit. Deeper deposits up to the economic limit of about 600 feet were developed and mined by shafts or inclines. At the Monument No. 2 mine, which produced more than half of the total production from the district, most ore was mined by open-pit methods.

The uranium deposits of Monument Valley have been studied by many geologists; more recent reports include those by Witkind and Thaden (1963), Young (1964), and Malan (1968).

As used in this paper, Shinarump channels are the courses of paleostreams which were incised into the underlying Moenkopi Formation and which were filled with fluvial sediments. Scours are the discontinuous, stream-incised, cut-and-fill components within the channels. These scours developed at stages during the lateral shifting of the main stream channel. Sediments in scours in the lower portions of channels are the hosts for the uranium deposits. Channels in Monument Valley are U-shaped in cross section, contain mainly sandstone and conglomerate, are quite narrow, and commonly contain only one ore-bearing scour. Not all scours in paleochannels contain uranium mineralization. Uranium deposits are primarily restricted to favorable carbonaceous sandstone and conglomerate beds in the lower part of the Shinarump Member of the Chinle Formation; however, in a few mines ore extends downward as much as 15 feet into underlying beds.

Ore bodies consist of closely-spaced, lenticular ore pods which are generally concordant with bedding. Single ore pods range from a few feet to a few hundred feet in length and from less than one foot to 12 feet in thickness. As viewed in plan, most ore deposits are linear. The ratio of length to width is commonly at least 5 to 1 and may reach 50 to 1. Deposits range in size from a few tons to approximately 800,000 tons of ore. About half of the deposits are smaller than 1,000 tons in size and all but two are smaller than 50,000 tons.

The deposits contain variable amounts of copper and vanadium. Ores from the Monument No. 2 mine contained an average of 1.40 percent V₂O₅ and little or no copper. In the other deposits for which some data are available, vanadium ranges from 0.22 percent to 0.81 percent and copper ranges from 0.29 percent to 2.50 percent; weighted averages
are 0.60 percent V_2O_5 and 0.71 percent copper. These averages are not representative, because they are based solely on production from mines for which the vanadium and copper content was recorded. In general, the vanadium content of ores decreases from east to west, but copper increases from east to west.

In the unoxidized parts of the Monument No. 2 mine, uraninite and coffinite are associated with vanadium minerals such as montroseite, corvusite, doloresite, and vanadium hydromica. Sulfides of iron, copper, and lead are also present. Oxidized ore minerals from this mine are tyuyamunite, carnotite, hewettite, and navajoite. All of these minerals are associated with oxides of iron. In other mines in Monument Valley, the suite of unoxidized minerals is the same as that at the Monument No. 2 mine, but copper sulfide minerals are more abundant, and montroseite is less abundant. The uranium minerals, torbernite, uranophane, uranopilite, betazippeite, and johannite have been identified in samples from oxidized deposits. Malachite, azurite, and hydrous copper and iron sulfates are common accessory minerals.

Calcium carbonate is present in ore mostly as cementing material in the sandstone host rock. In Monument Valley mines, calcium carbonate ranges from 1.4 percent to 10.3 percent and averages 4.6 percent. Calcium carbonate content generally is inversely proportional to vanadium content but it does not correlate with copper.

The Bluestone mine (not shown on figure 1) is located approximately five miles east of the Monument No. 2 mine on the flank of Comb Ridge. At this property uranium and copper minerals are disseminated in the Navajo Sandstone adjacent to a serpentine rubble dike at the northeast end of the Garnet Ridge igneous area. Tyuyamunite and voglite are the only uranium minerals that have been identified. Early in 1956, 56 tons averaging 0.22 percent U_3O_8 were produced from an open cut.
The Cameron area is on the southwest flank of the Black Mesa Basin. Here, the Chinle Formation crops out in a broad belt nearly parallel to the Little Colorado River. The main mining area forms a curved belt approximately 2 miles wide extending 6 miles north of Cameron along U.S. Highways 89 and 164, and 5 miles wide extending 18 miles southeast along the Little Colorado River (fig. 2). However, several additional deposits occur outside this area. The principal host rock in the area is the Petrified Forest Member. Underlying the Petrified Forest Member is the sandstone and mudstone member. The sandstone and mudstone unit has been included in the Shinarump by Akers and others (1962); however, recent mapping by the USGS in the Black Point area identifies this unit as a separate member (D. V. Haines, personal communication, 1970). Uranium deposits previously reported as occurring in the Shinarump are actually located in the sandstone and mudstone member.

Uranium was first reported in the Cameron area in 1950 in the Kayenta Formation of Early Jurassic (?) age. As a result of the discovery, the AEC employed Navajos to prospect the entire area. The first discovery of commercial importance was made by Charlie Huskon, an AEC prospector, in the Petrified Forest Member of the Chinle Formation in early 1952. Surface prospecting supplemented by airborne radiometric surveying led to the discovery of additional ore bodies in 1953. As the area developed, many deposits having no surface expression were located by shallow exploration drilling. Initial production from the area was in late 1950 from the Hosteen Nez property in the Kayenta Formation. Production reached a peak in 1957 and gradually declined until the latest shipment which was recorded in January 1963. During that period a total of 289,300 tons averaging 0.21 percent U₃O₈ and containing 1,211,800 pounds U₃O₈ were produced from 98 separate properties. Mining has been by open pits ranging in size from small shallow trenches containing a single mineralized fossil log to a large pit complex 2,400 feet long and 250 feet wide. Underground mining from the walls of the pits to recover additional ore was a common practice. Four vertical shafts were also used in the area.

The deposits have been described by Hinkley (1957), Bollin and Kerr (1958), and Chenoweth (in Akers et al., 1962). Chenoweth and Magleby (1971) prepared a map showing the location and relative sizes of the deposits, and Austin (1964) has described the mineralogy of the deposits. Sixty-seven deposits, that occur in the lower part of the Petrified Forest Member, have yielded 1,177,500 pounds U₃O₈ or
97 percent of the area's total production. The ore occurs within elongated, lenticular deposits of poorly consolidated, cross-stratified, fine- to medium-grained sandstone, clay-pellet sandstone, and clay-pellet conglomerate which contain varying amounts of carbonaceous matter, including carbonaceous fossil logs. The sandstone lenses were deposited in irregular depressions cut into bentonitic claystones and mudstones and are probable ancient fluvial channel fills. The maximum observed thickness of the lenses is approximately 35 feet; the average thickness is approximately 20 feet. The continuity of the sandstone lenses is poor, but individual lenses have been traced for more than a mile. Ore consists chiefly of secondary uranium minerals filling pore spaces in sandstone and in places uraniferous fossil logs. The ore tends to occur in abrupt depressions along channels or at changes in a channel's direction, and favors the more carbonaceous layers. Ore bodies are usually elongated parallel to the trend of the channels, but some ore bodies are oriented nearly normal to the sedimentary trends. Each ore body is encased in an alteration halo consisting of bleached sandstone and mudstone. Ore bodies and halos terminate abruptly downward against impervious mudstone. The most visible bleaching effect is a change from gray or occasionally red to yellowish or buff.

Ore bodies occur from the surface to a depth of 130 feet. As many as three ore zones may be present in 100 feet of section. Individual ore bodies range in size from a single mineralized fossil log to the Jack Daniels ore body, the largest known in the area, which was a nearly continuous body 450 by 300 feet containing 178,000 pounds U₃O₈. By comparison, the second largest deposit is the Charles Huskon 4-Paul Huskie 3 from which was produced 135,600 pounds U₃O₈ from a cluster of ore pods occurring in an area 1,000 by 550 feet. The most productive area is east of Cameron where 10 properties, within one square mile, have been the source of 264,100 pounds or 22 percent of the total production.

Twenty-seven deposits in the sandstone and mudstone member occur with carbonaceous material in a thin-bedded, cross-stratified, medium- to fine-grained sandstone in the upper 30 feet of the member. Uranium-bearing fossil logs are common. The largest deposit in this member is Huskon 11 from which 6,600 pounds U₃O₈ were produced. The three small deposits in the Kayenta Formation occur in fine-grained sandstone lenses in the middle part of the formation. Total production from the Kayenta Formation in the Cameron area is 550 pounds U₃O₈.
Figure 1. Mine locations, Monument Valley, Navajo and Apache Counties, Arizona and San Juan County, Utah.
Figure 2. Mine locations, Cameron area, Coconino County, Arizona.
The Riverview mine occurs in a breccia pipe located within the Moenkopi Formation. Blocks of sandstone lithologically similar to sandstone in the Shinarump Member of the Chinle Formation fill the top of the pipe, and uranium minerals occur in these sandstone blocks, as well as in a siltstone and mudstone breccia, derived from the Moenkopi (Chenoweth and Blakemore, 1961).

A characteristic feature of the Cameron ores is their complex mineralogy. Uraninite is present in the unoxidized zone and also occurs in and near unoxidized logs in the oxidized zone in association with pyrite and marcasite. Oxidation has produced a complex suite of uranium oxides, sulfates, silicates, phosphates, carbonates, molybdates, and rare vanadates (Austin, 1964). The yellowish-gray alteration associated with all deposits at or near the surface has been used as a prospecting guide. According to Austin (1964) this so-called bleaching is chiefly due to oxidation products of sulfides but some actual bleaching of the clay has occurred.

**Winslow-Holbrook-St. John's area**

Deposits similar to those near Cameron occur in the upper Little Colorado River drainage from near St. John's, Arizona, to the vicinity of Winslow, Arizona (table 1). The deposits, which are generally smaller than those at Cameron, occur in the sandstone lenses in the lower part and in the Sonsela Sandstone Bed of the Petrified Forest Member.

Many of the deposits were located in the early 1950s by prospectors who were exploring exposures of the Chinle which was known to be productive elsewhere. Over two dozen uranium-bearing outcrops were located, and the AEC drilled two of the more promising exposures (Gregg and Moore, 1955, 1956). During the period 1953 to 1960, 20 properties (table 1) produced 2,690 tons grading 0.15 percent U₃O₈ and containing 8,020 pounds U₃O₈. Mining methods used have included shallow open pits and trenches, rim cuts, and short underground adits. The most productive area is east of Holbrook in the SE 1/4 T. 18 N., R. 23 E. and NE 1/4, T. 17 N., R. 23 E., where seven properties produced 1,400 tons containing 0.21 percent U₃O₈ and 0.20 percent V₂O₅. Of this total, 86 percent came from the Ruth claims.

The uranium deposits occur in sandstone lenses that are generally less than 200 feet wide and 10 feet thick. Some of these lenses have been traced for a distance of nearly one-half mile. Within the sandstone lenses, uranium is nearly always
Table 1. Mine locations, Winslow-Holbrook-St. John's area, Navajo and Apache Counties, Arizona.

<table>
<thead>
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<th>PROPERTY NAME</th>
<th>SECTION</th>
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<th>R. (E)</th>
</tr>
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<td>20</td>
</tr>
<tr>
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<td>20</td>
</tr>
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<td>S 1/2, NW, SW</td>
<td>33</td>
<td>19</td>
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<td>NE, NW, SW</td>
<td>24</td>
<td>19</td>
</tr>
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<td>19</td>
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<td>1</td>
<td>18</td>
</tr>
<tr>
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<td>28</td>
<td>18</td>
</tr>
<tr>
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<td>33</td>
<td>18</td>
</tr>
<tr>
<td>Juanita 3</td>
<td>S 1/2, NW, SE</td>
<td>14</td>
<td>18</td>
</tr>
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<td>17</td>
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<tr>
<td>Ruth 4</td>
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<td>2</td>
<td>17</td>
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<tr>
<td>Mac 3</td>
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<td>4</td>
<td>17</td>
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<tr>
<td>Sunrise</td>
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</tr>
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<td>G &amp; C 1</td>
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associated with carbonaceous plant material, often in the form of fossil logs. Uranium minerals identified from the Ruth claims include metatorbernite, metazeunerite, uraninite, and coffinite (Gruner and others, 1954), and schroeckingerite, zippeite, and autunite (Gregg and Moore, 1955).

Chinle area
Uranium occurs in the Shinarump Member at the Zhéaly Tso property, 6 miles northeast of Chinle, Arizona, adjacent to Canyon de Chelly National Monument. At four locations in the NW 1/4, T. 5 N., R. 9 W., secondary yellow uranium minerals have been observed in association with copper carbonates and carbonaceous plant debris in sandstone lenses in the upper part of the Shinarump. Exploration drilling during the middle 1950s, however, failed to locate any commercial ore.

Deposits In The Morrison Formation
Exposures of the Morrison Formation in northeastern Arizona occur on the north and east sides of Black Mesa, on the periphery and within the Carrizo Mountains, and in the Lukachukai Mountains. The formation is composed of four members. In ascending order, they are the Salt Wash, Recapture, Westwater Canyon, and Brushy Basin. Major uranium deposits are restricted to the Salt Wash Member. All of the members are fluvial and intertongue with each other. Contacts are arbitrary and are based on lithologic differences.

Salt Wash Member - The Salt Wash consists of sandstone with lesser amounts of claystone and siltstone, which form resistant ledges, steep cliffs, and cap broad benches and mesas. The sandstones are fine- to very fine-grained, well sorted, with rounded to subrounded grains of predominantly quartz with some chert and feldspar. Colors of the sandstone vary from pale gray to greenish gray to light pink. These lenses are generally gently cross-stratified and obscurely interfinger with flat, even-bedded flaggy layers, some of which are ripple-marked. A few steeply cross-stratified, laminated or platy, medium-grained beds occur locally. Lenses of sandstone are generally between 10 and 40 feet thick. The sandstone is generally friable with interstitial clay. Locally the sandstone is very competent because of secondary calcite cement. Calcareous layers are common in or near ore deposits but are not confined to them.
The siltstone and claystone separating the sandstone lenses constitute between 5 to 50 percent of the member and are distributed throughout the member. They occur as (1) galls dispersed through the sandstone, (2) thin partings and contorted bands up to 3 inches thick, and (3) beds up to several feet thick. The claystone and siltstone vary in color from gray to greenish gray to reddish brown. There are no continuous siltstone and claystone layers as they pinch, swell, split, and coalesce along bedding.

Thin beds of hard, blocky limestone occur within the Salt Wash and probably represent a lacustrine environment. Fossil logs and carbonaceous plant debris are common throughout the Salt Wash. Fragmental particles and flakes of carbon form seams along the bedding and finer particles are disseminated throughout the sandstone.

The Salt Wash ranges in thickness from zero to approximately 220 feet. In the uranium areas it is usually at least 180 feet thick. North of the Carrizo Mountains the Salt Wash is absent. To the south, it cannot be recognized south of Sanostee, New Mexico, and on the east side of Black Mesa it is absent north of Rough Rock (fig. 5). According to Craig and others (1955), the Salt Wash was deposited by an aggrading, braided stream system on a massive alluvial fan system, the apex of which was near where the Colorado River now enters Arizona. Easterly and southeasterly sedimentary trends in the Carrizo and Lukachukai Mountains substantiate this concept. However, since the Salt Wash is absent by non-deposition both to the north and south, it appears that the Salt Wash of northeastern Arizona represents a separate lobe of the main fan which is farther to the north. This lobe of Salt Wash contains significant uranium deposits in the Carrizo and Lukachukai Mountains.

**Recapture Member** - Topographically, the Recapture forms a slope above the Salt Wash. The member consists of a series of lenticular sandstones and claystones generally darker in color than the Salt Wash. The sandstones are cross-stratified, fine- to coarse-grained, contain abundant feldspar, and are light-reddish brown to grayish pink in color. The interbedded claystones are typically reddish brown with some greenish gray colors present. Studies by Craig and others (1955) indicate that the major source of the Recapture was in west-central New Mexico. The member was deposited in an alluvial fan environment by northward flowing streams. Considerable intertonguing of the two members occurred in northeastern Arizona as the north flowing Recapture streams mingled with the east flowing Salt Wash streams. The Recapture ranges in thickness from 150 to 500 feet. It is generally thickest where the Salt Wash is the thinnest.
Sub-ore grade uranium deposits occur in the Recapture in the Lukachukai Mountains. Significant deposits occur in the upper Recapture west of Sanostee, New Mexico, about 22 miles southeast of the Lukachukai Mountains.

**Westwater Canyon Member** - The Westwater Canyon is a series of cliff-forming, light colored sandstones and mudstones which contrast with the underlying darker colored Recapture. The sandstones are medium- to coarse-grained, yellowish gray, grayish yellow in color and contain abundant feldspar. Some conglomeratic lenses are present. Interbedded with the lenses of sandstone are beds of greenish-gray claystone and siltstone. In northeastern Arizona the Westwater Canyon ranges from 150 to 265 feet in thickness.

At a few localities, north of the Carrizo Mountains, and south of the San Juan River in southeastern Utah, yellow secondary uranium minerals have been found in association with fossil logs in the Westwater Canyon. From one property, the Aneth 1, located 2 1/2 miles south of Aneth, Utah, a small shipment of ore was made in 1955. In general, the Westwater Canyon of the Carrizo Mountains area is similar to the Westwater Canyon in the Grants mineral belt, except at Grants it contains more organic material and more feldspar.

**Brushy Basin Member** - The Brushy Basin generally forms a steep slope above the Westwater. It is composed of a series of greenish-gray, pale-green, pink, and grayish-orange claystones and siltstones. Minor thin beds of fine- to medium-grained sandstone, conglomerate, and limestone are present. Silicification of these beds is common. The Brushy Basin ranges in thickness from zero to approximately 150 feet. Although no uranium deposits are known in the Brushy Basin in northeastern Arizona, the large amount of volcanic debris it contains may have been the source of uranium in the Salt Wash (Nestler and Chenoweth, 1958).

**Lukachukai Mountains**

The Lukachukai Mountains are the northwest spur of the Chuska Mountains and are on the northern tip of the Defiance Uplift. Lukachukai Pass on the road between Red Rock and Lukachukai, Arizona, separates them from the main Chuska range. A flat-topped ridge with an elevation of approximately 8,800 feet forms the main mountain mass. Finger-like mesas and deep, steep-walled canyons form rugged topography on the perimeter of the mountains. Except where they join the Chuskas, the Lukachukais terminate as precipitous cliffs.
The finger-like mesas were named and numbered as such by AEC personnel in late 1950. The prominent mesas on the north side of the mountains are numbered I through VII toward their northwest terminus at Mexican Cry Mesa. The southside mesas bear such descriptive names as Two Prong, Camp, Cisco, Three Point, Knife Edge, Bare Rock, Flag, Step, Fall Down, Navajo Chair, and Thirsty. In general, the mines are named for the mesas on which they occur and hence such minor divisions as Mesas I 1/2, I 3/4, II 1/2, and IV 1/2 do occur on the north side (fig. 3). Access to the mines is by a system of unimproved roads leading from Cove, Arizona.

Uranium-bearing outcrops in the vicinity of Mesa I were brought to the attention of prospectors from Colorado by local Navajos in 1949. An access road was built up Mesa I and production began in early 1950. In September 1950, the AEC began the first drilling project which was followed by five others that continued intermittently to August 1955. During this time, mine operators expanded exploration and development activities, and production increased steadily. Production reached its peak in 1960 and began to decline slowly until the last shipment was recorded in May 1968. During these 19 years, some 50 separate mines produced 724,800 tons of ore grading 0.24 percent U₃O₈ and 1.02 percent V₂O₅ and containing 3,483,300 pounds U₃O₈ and 14,730,100 pounds V₂O₅. Although some shallow or exposed ore bodies in the mountains have been successfully mined by stripping and open-pit methods, most ore bodies are mined underground by the room and pillar method, or modifications of it.

The ore bodies have been described by Nestler and Chenoweth (1958) and Chenoweth (1967). Paleodrainage patterns of the Salt Wash streams have been described by Stokes (1954). Dare (1959 and 1961) reported on two companies' operations and gives an excellent review of the problems and costs.

The mountains are capped by the Chuska Sandstone of Early Tertiary age which unconformably overlies a wedge of the Morrison Formation. The Salt Wash crops out continuously around the mountains. East of Mesa I and south of Two Prong Mesa, it has been removed by pre-Chuska erosion. In all, only 12.5 square miles of the mountains are underlain by this member of the Morrison.

The dominate structural feature of the mountains is the Chuska syncline. The Chuska syncline is sharply asymmetric. The steeply dipping limb of the syncline faces southwest opposing the regional dip of the Defiance uplift. The axis of the Toadlena...
Figure 3. Mine locations, Lukachukai Mountains, Apache County, Arizona
anticline, to the northeast, nearly parallels that of the syncline and plunges northwest. All ore bodies are on the southwest limb of the Chuska syncline with the exception of several large deposits on Mesa I and a small deposit on the northern tip of Mesa V which are on the northeastern limb of the syncline.

Ore bodies occur some 30 to 80 feet above the base of the Salt Wash which is roughly the middle half of the member. All of the significant deposits are located in a well-defined belt which trends nearly north-south across the southeast end of the mountains (Chenoweth, 1969). This belt accounts for 99.6 percent of the total production and includes an area of 6.5 square miles. The ore bodies are elongate and horizontally lenticular in shape and consist of one or more ore pods surrounded or separated by protore. The composite length of ore bodies consisting of two or more ore pods separated by protore ranges up to 1,100 feet; individual ore pods range up to 350 feet in length. The length is usually at least three times the width and is parallel to paleostream depositional trends measured in and near the ore bodies. Thicknesses of the ore bodies range from 1 to 22 feet. Claystone and/or siltstone beds nearly always underlie and frequently overlie the host sandstone units.

Ore occurs most commonly in trough-type, cross-stratified sandstone which fills scours and channels in the underlying claystone. Lithofacies maps and mine mapping by Nestler and Chenoweth (1958) show that ore bodies are restricted to areas of rapid lateral color change which in general are also areas of rapid change in the ratio of mudstone to sandstone. It is common for the elongation of ore pods to deviate from the paleostream depositional trend and parallel the prominent joint set. This feature suggests some redistribution of the ore.

One of the most striking ore trends in the mountains is the trend from the Mesa III mine through the Mesa II 1/2 mine to the north ore bodies of the Mesa II (P-21) mine. Striking N. 25° W. and extending for 4,200 feet with a width of 200 to 400 feet, this trend was the source of approximately 180,000 tons averaging 0.24 percent \( U_3O_8 \) and 1.08 percent \( V_2O_5 \). The ore bodies occurred in a 25- to 30-foot thick sandstone lense, the base of which is approximately 50 feet above the Salt Wash-Bluff contact.

Tyuyamunite, the calcium uranium vanadate, is the most common ore mineral. It occurs irregularly disseminated, concentrated in lenses, or distributed in bands. It may fill the sand interstices, or only coat sand grains, or it may replace calcite and
carbon. Other vanadium minerals include corvusite, pascoite, hewettite, metarossite, vanadium clays, and possibly montroseite (S. R. Austin, personal communication, 1967). In addition, Gruner and others (1954) identified the vanadium minerals melanovanadite and hummerite. Laverty and Gross (1956) identified uraninite as replacing carbonaceous material and as a cement in some ore bodies that are not completely oxidized. Calcite is the usual cementing agent in the ore bodies. Pyrite and iron oxides are present.

Carrizo Mountains
The Carrizo Mountains are in extreme northeastern Arizona on the northeast margin of the Black Mesa Basin. The mountains are an irregularly-shaped intrusive mass composed of a central stock and several sills of light-gray diorite porphyry that have been injected laterally into the surrounding sedimentary rocks. The mountains are about 13 miles in diameter and rise 2,000 to 3,000 feet above the surrounding plain. Pastora Peak, elevation 9,420 feet, is the highest point in the Carrizos. Access to the mining areas is by a network of unimproved dirt roads that crisscross the area surrounding the mountains.

The uranium-bearing vanadium deposits of the Carrizo Mountains were discovered about 1918 by John Wade. By 1920, Wade had 41 claims in the Carrizo Mountains (personal communication, 1955). Because of the lack of demand for domestic vanadium, little mining was done until 1942, when war conditions increased the demand for vanadium ores. In December 1941, the Vanadium Corporation of America leased 17 plots in the northwest Carrizo and Eurida Mesa areas, and in July 1942 they also leased 12 plots in the east Carrizo area. Early in 1942, Wade, Curran, and Company leased 14 plots in the east, northwest, west, and south Carrizos. Mining by these two companies was from surface exposures on the east, northwest, and west sides of the mountains. According to Stokes (1951), during the period May 1942 through February 1944, the Carrizos yielded approximately 22,000 tons averaging 2.25 percent V$_2$O$_5$.

Mining activity resumed in 1948 with the emphasis on uranium and continued until June 1968 when the latest shipment was recorded. During this period 120,600 tons grading 0.22 percent U$_3$O$_8$ and 1.93 percent V$_2$O$_5$ and containing 525,800 pounds U$_3$O$_8$ and 4,659,200 pounds V$_2$O$_5$ were produced from over 100 properties (fig. 4). Mining methods used include adits from mesa rims, inclined shafts, and a few vertical shafts. Surface exposures were exploited using rim cuts, trenches, and small open pits. In the larger underground mines, room and pillar methods or modifications of it were used.
Figure 4. Mine locations, Carrizo Mountains, Apache County, Arizona and San Juan County, New Mexico.
The ore deposits of the Carrizo Mountains were first studied by geologists of the Union Mines Development Corporation who evaluated the uranium resources of the area for the Manhattan Engineer District. The results of their appraisal are summarized by Webber (1943), Coleman (1944), Eakland (1946), and Harshbarger (1946). In the 1940s, the area was mapped in reconnaissance and the ore deposits studied by the USGS as part of the strategic minerals program. Some results of their work have been published by Stokes (1951). The first detailed geologic map of the area was published by Strobell (1956). Stokes (1954) studied the relation of sedimentary trends and structure to uranium deposits in three areas of the Carrizos. As the result of AEC investigation, the deposits in more productive areas have been described by Chenoweth (1955), Masters and others (1955), and Blagbrough and others (1959).

In general, exposures of the Salt Wash Member dip away from the Carrizo intrusive. On the east side of the mountains the Salt Wash outcrop forms a belt from Red Rock to Beclabito roughly paralleling the Arizona-New Mexico state line. South of Beclabito it rims Beclabito dome. To the east of the dome, a narrow band of Salt Wash is exposed on the margin of the intrusive. On the north side of the mountains there is a large exposure of the upper Salt Wash southwest of the Four Corners. The lower Salt Wash crops out in a small area at the foot of the mountains and in separate exposures interbedded with igneous sills in the northeastern part of the intrusive. The Toh Atin anticline exposes the lower Salt Wash in the northwest Carrizos. The large amount of Salt Wash north of the anticline is largely covered with dune sand and the lower Salt Wash is exposed near the Utah line. West and south of the mountains the Salt Wash caps numerous mesas. Within the intrusive discontinuous outcrops occur in the central portion of the mountains.

The uranium deposits generally occur in clusters. Because of the clustering of deposits on the northwest, north, and east flanks of the mountains, these areas have been designated localities. There are also the west and south localities which do not contain the clusters present in the other localities. Isolated deposits are known in all of the localities. Important features of the five localities are given in table 2.

The Carrizo ore bodies are similar to those in the Lukachukai Mountains except that they are smaller and contain more vanadium. The vanadium to uranium ratio of the Lukachukai ores is 4:1 whereas the ratio for the Carrizo ores is 9:1. Ore bodies
Table 2. Significant features of the deposits in the Carrizo Mountains.

<table>
<thead>
<tr>
<th>LOCALITY</th>
<th>NO. OF MAP NOS. (FIG. 4)</th>
<th>TOTAL PRODUCTION</th>
<th>LOCATION OF ORE ZONES (FT. ABOVE Jb-Jms)</th>
<th>NAME</th>
<th>MOST PRODUCTIVE AREA</th>
<th>TONS</th>
<th>%U₃O₈</th>
<th>%V₂O₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>45 59-103</td>
<td>47,100</td>
<td>30-80</td>
<td>King Tutt Mesa 1.4 sq. miles</td>
<td>27,200</td>
<td>0.24</td>
<td>2.48</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>7 53-58</td>
<td>3,700</td>
<td>30-40</td>
<td>--</td>
<td>52 acres</td>
<td>11,000</td>
<td>0.21</td>
<td>1.54</td>
</tr>
<tr>
<td>Northwest</td>
<td>36 1-36</td>
<td>27,400</td>
<td>1-40</td>
<td>Plot 6</td>
<td>52 acres</td>
<td>11,000</td>
<td>0.20</td>
<td>1.52</td>
</tr>
<tr>
<td>West</td>
<td>11 37-47</td>
<td>2,200</td>
<td>40-95</td>
<td>--</td>
<td>52 acres</td>
<td>11,000</td>
<td>0.21</td>
<td>1.54</td>
</tr>
<tr>
<td>South</td>
<td>5 48-52</td>
<td>40,200</td>
<td>20-100</td>
<td>Cove Mesa 0.76 sq. miles</td>
<td>38,800</td>
<td>0.22</td>
<td>1.61</td>
<td></td>
</tr>
</tbody>
</table>

1/ Does not include production during 1940s from Plot 3
2/ Does not include 2,500 tons at 0.15% U₃O₈ and 1.86% V₂O₅ produced in 1942-44 (Harshbarger, 1946)
and clusters of ore bodies are elongated parallel to paleostream channels and re-
distribution of ore along fractures is not as noticeable in the Carrizos as in the
Lukachukais. Also, ore rolls are common in the Carrizo deposits.

Tyuyamunite and metatyamunite are the only uranium minerals identified in the Carrizo
deposits, Gruner and others (1954), Corey (1956, 1958), and S. R. Austin (written
communication, 1967). Vanadium clay and montroseite are present. These minerals
have been oxidized to form a large number of secondary vanadium minerals which in-
clude sherwoodite, duttonite (?), hewettite, metahewettite, rossite, metarossite,
and hendersonite. All of these minerals were identified by Corey (1958) in her
studies of the Nelson Point mine. The vanadium minerals pascoite, volborthite, and
montrosite also have been identified by Corey (1956) from the Martin mine. Calcite
is a common cementing agent in ore. Pyrite, iron oxides, and gypsum may also be
present.

Field relationships and the Zona 1 and adjacent mines indicate the intrusion of the
sills faulted and fractured the existing ore deposits in the Salt Wash. Paragenetic
studies by E. B. Gross (written communication, 1954) indicate that silicification of
the Salt Wash took place after deposition of the uranium and vanadium minerals. Both
field and laboratory evidence indicate that the intrusion of the Carrizo laccolith
took place after the deposition of the uranium-vanadium deposits.

Chilchinbito area
Uranium occurs in the Salt Wash Member at the northeast foot of Black Mesa between
Chilchinbito and Rough Rock, Arizona, where Navajo prospectors discovered uranium-
bearing outcrops in late 1950. The AEC rim stripped and drilled behind the more
promising exposures in 1952 and 1953 (Anthony, 1956). During the 1951 to 1958
period, several small shipments were made from two properties (fig. 5). Total pro-
duction is 123 tons containing 0.74 percent U₃O₈ and 0.03 percent V₂O₅. The grade
of individual shipments has ranged from 0.18 to 1.79 percent U₃O₈.

The Salt Wash in the Chilchinbito area consists of approximately 130 feet of inter-
bedded fine- to very fine-grained grayish-brown sandstone and gray, green, and
reddish-brown siltstone and mudstone. Secondary uranium minerals are associated
with carbonaceous fossil logs and other plant debris in sandstone lenses 10 to 40
feet above the base of the Salt Wash. Fossil logs, observed during mining operations,
Figure 5. Mine locations, Chilchinbito and Black Mesa areas, Apache County, Arizona.
have been at least 14 inches in diameter and over 10 feet in length. Calcite crystals associated with the logs were responsible for the ore shipments averaging 31 percent CaCO₃. Mining has been entirely by shallow rim cuts.

**Deposits In The Toreva Formation**

Rocks of the Mesaverde Group of Upper Cretaceous age occur in the central portion of the Black Mesa Basin. Repenning and Page (1956) subdivided these rocks into three formations. The formations in ascending order are: Toreva Formation, Wepo Formation, and Yale Point Sandstone. They represent a complex intertonguing of marine and non-marine beds.

Uranium deposits are known in the Toreva Formation in the northeastern corner of Black Mesa in the Lohali Point-Yale Point area. The Toreva Formation in the Yale Point area is composed of the main ledge which is separated from an upper cliff-forming sandstone by a marine tongue of the Mancos Shale. South of Yale Point, the tongue of Mancos Shale pinches out and a non-marine tongue of the Wepo Formation, at a slightly higher stratigraphic horizon, separate the main ledge of the Toreva from the upper cliff-forming sandstone. All of the uranium deposits occur in the main ledge of the Toreva, a name used by O'Sullivan and others (1972) to distinguish this unit from the lower sandstone member of the Toreva found elsewhere. The main ledge consists of 140 to 170 feet of fine- to medium-grained sandstone with lenses of coarse- to very coarse-arkosic sandstone in the upper part. Small amounts of coal, carbonaceous shale, and siltstone occur in the beds in the upper part of the main ledge.

Uranium-bearing outcrops in the vicinity of Burnt Corn Wash was brought to the attention of the AEC in January 1954. Following this discovery, an AEC ground and airborne reconnaissance of the area was made and some 25 radioactive anomalies were located in Lohali Point-Yale Point area. Also three anomalies were found in the upper drainage of East and West Polacca Washes and two anomalies were indicated along Oraibi Wash, north of Pinon, Arizona (Clinton, 1956). Although several of the anomalies were caused by radioactive heavy mineral accumulations, many of the anomalies were developed into prospects and mines. During the 1954 to 1968 period, 16,800 tons grading 0.17 percent U₃O₈ and containing 55,700 pounds U₃O₈ were produced from 13 properties. Ore was mined by shallow open pits, rim cuts, and in two places by underground methods. With the exception of two properties near Yale Point, all of the production came from properties located on both sides of the upper drainage of Burnt Corn Wash (fig. 5).
The uranium deposits occur in a quartzose zone in the upper part of the main ledge of the Toreva. Lenses of carbonaceous shale and siltstone are common in the ore-bearing zone. Some uranium occurs in the carbonaceous material but the majority of it occurs disseminated in the sandstone. In general, the ore occurs immediately below carbonaceous beds. The deposits consist of pods of ore grade material surrounded by protore. Clusters of these pods may occur to form an ore deposit within an area of 400 feet by 100 feet, having an average thickness of less than 2 feet.

Uranium minerals include tyuyamunite and metatyuyamunite, and vanadium minerals include vanadium clay, metahewettite, and melanovanadite (E. B. Gross, written communication, 1956). Production records on the initial 4,750 tons of ore shipped indicated an average vanadium content of 0.27 percent $V_2O_5$ and an average uranium content of 0.24 percent $U_3O_8$.

**Deposits In The Bidahochi Formation**

The Bidahochi Formation of Pliocene age is present in the southeastern part of the Black Mesa Basin and unconformably overlies older rocks. The Bidahochi consists of fluvial and lacustrine sedimentary rocks and basaltic volcanic rocks. Repenning and Irwin (1954) have subdivided the formation into three members: a predominantly lacustine lower member, a medial volcanic member, and an upper, chiefly fluvial, member. Associated with the volcanic member are approximately 150 diatremes of the Hopi Buttes volcanic field which have been described in detail by Hack (1942). Uranium in the Hopi Buttes is associated with these diatremes.

Uranium was first discovered in the Hopi Buttes in 1952 by E. M. Shoemaker of the USGS. Airborne radiometric reconnaissance by the AEC and private interests showed that the occurrence of radioactivity in the diatremes was widespread. Detailed geologic studies by the USGS have been summarized by Shoemaker and others (1962). Minor AEC investigations have been reported on by Fair (1955) and Lowell (1956).

Uranium occurrences are restricted to diatremes containing bedded carbonate rocks. The uranium content of the carbonate rocks is low, generally 0.001 to 0.02 percent $U_3O_8$. Uranium, of higher grade, occurs in non-volcanic clastic rocks, tuffs, and sedimentary rocks derived from the wall of the vents within the diatremes.
Although 35 diatremes contain significant uranium, from only one, Seth-la-kai, located five miles northeast of Indian Wells, Arizona, has ore grade material been produced. The Morale property at this diatreme produced 192 tons grading 0.15 percent $U_3O_8$ during 1954 to 1959. Unidentified uranium minerals occur in a 6- to 8-inch thick, coarse-grained, non-volcanic sandstone and in adjacent calcareous tuff beds within the diatreme. The high phosphate content of the Morale ore, 0.75 to 1.00 percent $P_2O_5$, made it unacceptable to processing in an alkaline leach circuit. The ore was mined from a rim cut and a short adit on the southeast rim of the diatreme.

Schroeckingerite has been identified by Shoemaker and others (1962) at the Hoskie Tso claim at a diatreme 2 miles southeast of Indian Wells, and carnotite has been identified by Gruner and Smith (1955) at the Horseshoe diatreme, 9 miles north of Indian Wells.

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