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GEOLOGY OF URANIUM DEPOSITS IN TRIASSIC ROCKS OF THE COLORADO PLATEAU *

By

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By W. I. Finch

ABSTRACT

Important uranium deposits are widely distributed in the Triassic rocks of the Colorado Plateau region, and have been the second most productive domestic source of uranium. Vanadium, copper, and radium have been produced from these uranium ores during various periods of mining in the past 50 years.

Most of the deposits in Triassic rocks are in the Shinarump and Moss Back members of the Chinle formation, but some important deposits are, also, in the other lower members of the Chinle, particularly in beds within 50 feet of the mid-Triassic unconformity. In northeastern Arizona, eastern Utah, and western Colorado three mineral belts have been outlined, each bounded by a pinchout. These belts, which contain about 20 percent of the areas underlain by Chinle rocks, are the Monument Valley belt, the East White Canyon belt, and the Moab belt.

The chief unoxidized uranium minerals, uraninite and coffinite, and oxidized uranium minerals, carnotite and tyuyamunite, impregnate the rocks, forming disseminated ores. Fossil wood and interstitial cement replaced by these minerals and the associated iron and copper minerals constitute the high-grade ore. Most of the ore averages between 0.20 and 0.30 percent U_3O_8 and some ores average between 1 and 2 percent V_2O_5 or between 1 and 2 percent Cu.

The ore bodies are spottily distributed and form irregular tabular and concretionary masses that lie essentially parallel to the bedding of channels and lenses filled with coarse clastic material. They range in content from a few tons to more than a hundred thousand tons.

It is believed that in early Tertiary time ground water leached uranium and other ore metals from syngenetic concentrations in the overlying mudstone beds or in the ore-bearing rocks themselves and redeposited the metals in favorable sedimentary and tectonic structures.

INTRODUCTION

About one-quarter of the uranium that has been produced in the Colorado Plateau region has come from Triassic sedimentary rocks. The U. S. Geological Survey, on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission, has therefore made a reconnaissance geologic appraisal of the deposits in the Triassic rocks of the Colorado Plateaus, particularly of those in the Shinarump and Moss Back members of the Chinle formation, in which most of the deposits occur.

The primary object of this work was to aid prospectors and mining men in finding and exploiting new deposits of uranium-bearing ores. With this object in view, a study was made of the distribution and geologic relations of known deposits in the principal uranium-producing districts of the Colorado Plateau region in Utah, Arizona, and Colorado (fig. 1). Previous work on the vanadium-uranium deposits in the Late Jurassic Morrison formation was useful in helping to determine what factors are common to all the uranium-bearing deposits of this region.

The deposits in the Morrison were studied between September 1949 and July 1951, and those in the Triassic rocks between July 1951 and October 1953. Although most of this work was in the nature of reconnaissance, it included the detailed mapping of selected mines, one in each of the following areas: Monument Valley, White Canyon, the Circle Cliffs, the San Rafael Swell, and Seven Mile Canyon.

Credit for the results of this work must be shared with more than a dozen field assistants who rendered efficient service, and with geologists of the Atomic Energy Commission and the Geological Survey who contributed helpful discussion of problems relating to uranium ores.

HISTORY OF MINING AND PRODUCTION

Radioactive minerals on the Colorado Plateau were first discovered in the Morrison formation near Roc Creek in Montrose County, Colo., in 1898, and in the early 1900's carnotite was discovered in Triassic rocks at Temple Mountain, in the San Rafael Swell, in Emery County, Utah. During the period 1920-40, while the Geological Survey was mapping a large part of eastern Utah and northeastern Arizona in connection with a general reconnaissance for oil and gas, uranium, vanadium, and copper minerals were noted in

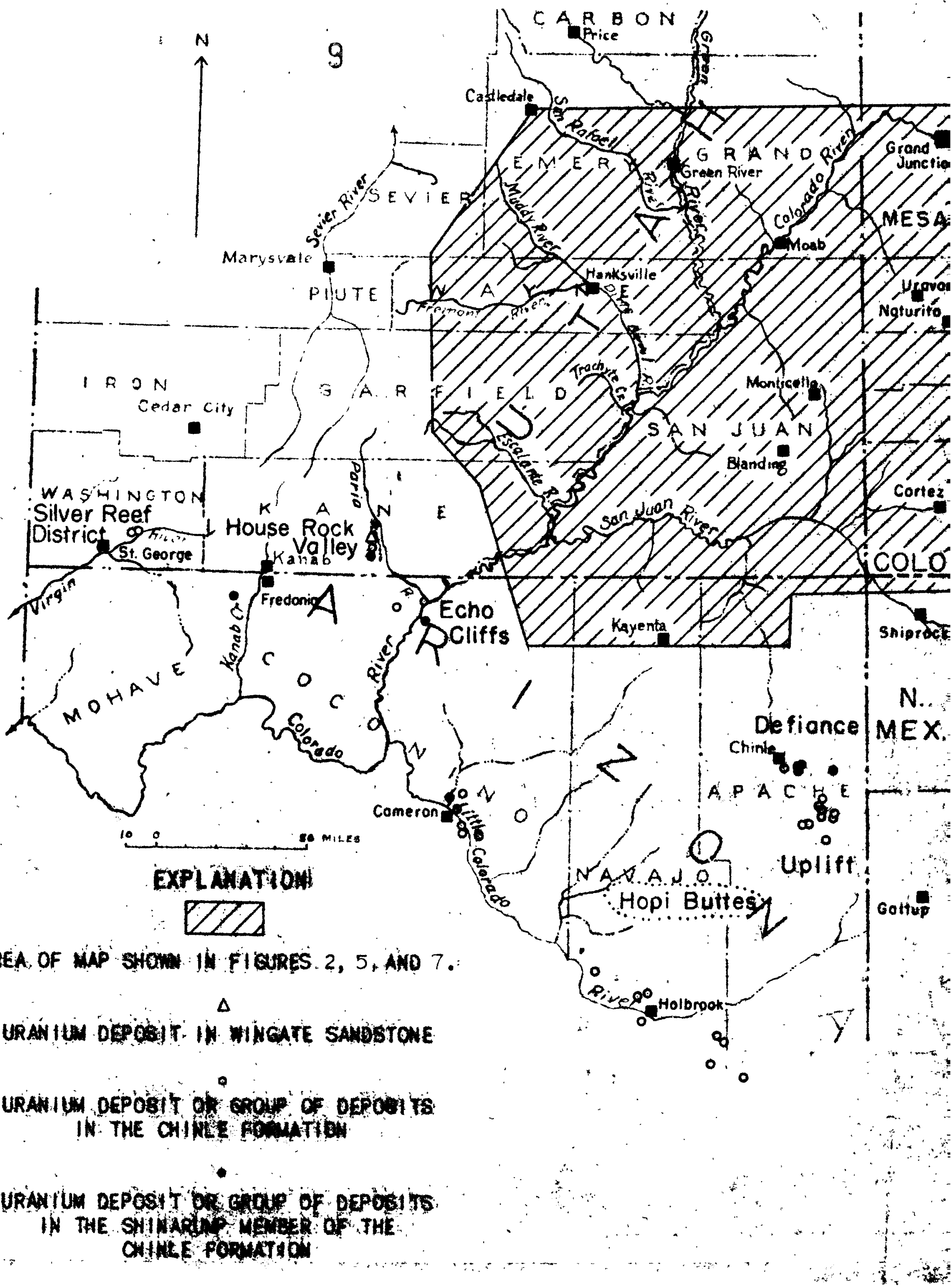

Figure 1. INDEX MAP OF PART OF THE COLORADO PLATEAU REGION SHOWING THE LOCATION OF AREA REPRESENTED IN FIGURES 2, 5, AND 7, AND DISTRIBUTION OF URANIUM DEPOSITS IN TRIASSIC ROCKS OUTSIDE THAT AREA.

many places throughout the region, especially near the Moenkopi-Chinle contact (Baker, 1933, 1935, and 1946; Dane, 1935; Gilluly, 1929; Gregory, 1938; Gregory and Moore, 1931; McKnight, 1940). Until 1948 these occurrences, except for a few copper prospects, were regarded as only of academic interest. A large vanadium-uranium deposit had been found in 1921 (Butler and Allen, 1921) in the Shinarump member of the Chinle in Monument Valley; this deposit was worked in 1942 in the Monument No. 2 mine, but its importance was not understood until after 1948.

Radioactive deposits on the Colorado Plateau have been mined during three periods, first for radium, then for vanadium, and in recent years chiefly for uranium; and deposits in Triassic formations contributed ore during all three periods. During World War I several hundred tons of high-grade ore were produced for radium from Triassic rocks at Temple Mountain, Utah (Hess, 1922), but mining of radioactive minerals in the Colorado Plateau region came to an end in 1923, when deposits in the Belgian Congo, Africa, became the world's source for radium.

From the early 1930's until 1945, the radioactive ores were mined principally for vanadium, and during this period, a few thousand tons of vanadium ore was produced from the Shinarump member of the Chinle in Monument Valley. Mining of radioactive deposits on the Colorado Plateau was resumed for a third time in 1948, when the Government began its program of buying and searching for uranium ores. The uranium ore produced on the Colorado Plateau during 1948 came largely from Triassic rocks at Temple Mountain and in Monument Valley. From 1949 to 1953, the Triassic rocks yielded about 20 percent of the uranium ore produced on the Plateau, and in 1954 about 30 percent. The chief metal sought from 1948 to the present was, of course, uranium, but large amounts of vanadium and some copper have been extracted from the uranium ores. Radium is no longer recovered. By the end of 1953 several hundred thousand tons of uranium ore had been produced from Triassic rocks.

In 1948, when the "rush" for uranium ore began, much of the outcrop area of Triassic rocks was inaccessible to wheeled vehicles except by way of rough roads through parts of Monument Valley, White Canyon, the Capitol Reef National Monument, the San Rafael Swell, and Indian Creek Valley. By 1951, however, prospecting had extended into most areas where Triassic rocks were exposed, old trails had been improved, some good roads had been built, and several mines had been opened. The most important event during the period 1948 to 1951 was the rediscovery of uranium ore in an old copper-uranium prospect, now known as the Happy Jack mine, in White Canyon, San Juan County, Utah. With the discovery of several bonanzas in the Big Indian Wash area of the county, in 1952 and 1953, prospecting and exploration by private enterprise throughout the plateau region attained gold-rush proportions. By the end of 1953, nearly all the outcrops of Triassic rocks had been prospected, many benches had been explored by drilling, and about 55 mines in Triassic rocks were in operation.

GEOLOGIC SETTING

The sedimentary rocks on the Colorado Plateau are of Late Paleozoic to Tertiary age and have an aggregate maximum thickness of over 15,000 feet. The Triassic rocks, which occupy the middle part of the stratigraphic column, range in total thickness from 50 to 2,500 feet. For the most part the sedimentary strata lie flat, and, as is common in arid climates they have been eroded into mesas bounded by deeply incised canyons. In some places, however, they have been folded into monoclines, anticlines, and domes, which have been eroded to form monoclinal ridges and inward-facing walls of rock along strike valleys or along rims of oval depressions; or they have been broken by high-angle normal faults which have been eroded to form scarps of valleys. Several isolated small groups of mountains have been carved from laccoliths and stocks of Tertiary igneous rocks.

Stratigraphy

Although uranium deposits occur on the Colorado Plateau in over a score of formations of Carboniferous to Tertiary age (Finch, 1955), the most productive ones are in the Chinle formation of Triassic age, and the Morrison formation of Jurassic age. A generalized section of Permian, Triassic, and Jurassic rocks is given in table 1, but only the Triassic rocks need here be described further.

Table 1. Generalized section of Permian, Triassic, and Jurassic rocks of parts of Utah, Arizona, and Colorado

System	Group	Formation	Thickness (feet)	Character and distribution
Jurassic		Morrison formation	300 - 500	Brushy Basin shale member; varicolored mudstone, with some sandstone lenses; forms slopes; widespread.
			200 - 400	Salt Wash sandstone member; light-colored sandstone and red mudstone; forms cliffs and benches; widespread.
	San Rafael group	Summerville formation	0 - 400	Red and gray shale, with thin beds of sandstone; forms slopes; thickens westward.
		Curtis formation	0 - 250	Glauconitic sandstone, greenish shale, and gypsum; present only in central Utah.
		Entrada sandstone	0 -1,000	Light-colored, massive, cliff-forming sandstone in Colorado and eastern Utah; thickens westward and becomes red earthy sandstone.
		Carmel formation	0 - 600	Red earthy sandstone in Colorado and eastern Utah; thickens westward and becomes gray and red shale, limestone, and gypsum.
Jurassic and Jurassic (?)	Glen Canyon group	Navajo sandstone	0 -2,000	Light-colored massive sandstone; cliff-forming; thins to extinction in western Colorado; thickens westward.
Jurassic (?)		Kayenta formation	0 - 300	Red sandstone, irregularly bedded; bench-forming; absent in southeastern part of region.
Triassic		Wingate sandstone	0 - 500	Red massive sandstone; cliff-forming; absent in southwestern part of region.
		Chinle formation	0 -1,500	Main body of Chinle: includes members above the Shinarump or Moss Back, commonly divided into upper and lower; red, gray, and green mudstone, gray sandstone and limestone; forms slopes and ledges; thickens southward.
			0 - 150	Moss Back member: light-colored sandstone and conglomerate; some channels, forms cliff; absent in Arizona and southern Utah.
			0 - 250	Mudstone unit below the Moss Back: green, gray, and purple mudstone and siltstone, scattered sandstone lenses; forms slope; grades laterally into equivalent units where Moss Back is absent; its base is the mid-Triassic unconformity where the Shinarump is absent.
			0 - 250	Shinarump member: light-colored sandstone and conglomerate; channels common, forms cliff; absent in Colorado and northern Utah.
		Mid-Triassic unconformity		
		Moenkopi formation	0 -1,800	Reddish-brown and light-colored siltstone and sandstone, light-colored limestone horizontally and ripple-laminated; thickens westward.
Permian		Cutler formation	0 -1,500	Brown to red sandstone and red to purplish arkose, cross-laminated.
Pennsylvanian and Permian (?)		Rico formation	0 - 600	Brown to red and purple sandstone containing several fossiliferous limestone beds, thin-bedded.

Moenkopi formation

The Moenkopi formation, which is of Early and Middle(?) Triassic age, crops out mainly in eastern Utah and northern Arizona. Its base rests unconformably on Permian strata, but there are few places at which this unconformity is well displayed. The upper surface of the Moenkopi, which corresponds with part of the mid-Triassic unconformity (fig. 2), has been eroded by streams that may have deposited the overlying Chinle formation. In Monument Valley some of these streams cut through the Moenkopi into Permian strata (fig. 3), and in western Colorado and eastern Utah the Moenkopi pinches out irregularly along the flanks of salt-dome structures, which are 10 to 60 miles long, and along the west flank of the Uncompahgre Plateau, a large positive area until the end of the Triassic. The Moenkopi is, generally, only a few hundred feet thick, and in southwestern Utah it attains a maximum thickness of nearly 1,800 feet.

The Moenkopi formation generally consists of red to chocolate-brown claystone, siltstone, and fine-grained silty and clayey sandstone, and it forms mainly steep slopes, but some sandstone beds form persistent ledges or cap small buttes and mesas. Especially distinctive are ripple-marked micaceous sandstone and siltstone, which are commonly thin-bedded. Very light colored beds occur in some places, notably in the San Rafael Swell and in parts of the area between the Green and Colorado Rivers. The formation also includes limestone strata; in the San Rafael Swell, the Sinbad limestone member is well developed.

FIGURE 3.--View looking southeast toward Comb Ridge showing the nature of the mid-Triassic unconformity at the Monument No. 2 mine, in Monument Valley, Apache County, Arizona. Here the bottom of the Monument No. 2 channel rests on the De Chelly sandstone member of the Cutler formation. Ꞧcs - Shinarump member of the Chinle, Ꞧm - Moenkopi formation, Pc - Cutler formation. Photograph from a kodachrome taken by T. L. Finnell.

For a foot or more below the mid-Triassic unconformity, the color of the sandstone in the Moenkopi is generally altered from red to chocolate brown to light brown, and that of the mudstone to gray or green. Uranium, vanadium, and copper minerals are widely distributed in the upper part of this altered zone, but they are mined only with contiguous ores in the overlying Chinle. One uranium ore deposit has been found in the Moenkopi, and it is about 50 feet below the altered zone.

Mid-Triassic unconformity

The most important horizon-marker in the Triassic rocks of the Colorado Plateau region is a widespread erosion surface at the base of the Chinle formation, that has been called the mid-Triassic unconformity. _/

_/ Stewart, J. H., in preparation, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull.

There is generally no marked difference in dip between the Moenkopi and the Chinle, and the old erosion surface that marks the unconformity is most conspicuous in places where it is immediately overlain by the Shinarump member or the Moss Back member of the Chinle. Both of these units are so coarse-grained as to be sharply distinct from the finer-grained rocks which always underlie them, and by tracing their basal contacts it has been found that they rest on an uneven surface, scored with channels up to 125 feet in depth. In most places the Chinle rests on the Moenkopi, but some of the channels filled with Shinarump rocks cut through the Moenkopi (fig. 3).

The mid-Triassic unconformity is not only of outstanding interest for students of geology but is a feature that prospectors and miners need to be able to recognize; for the most productive uranium deposits that have been found in Triassic rocks of the Colorado Plateau region are near this pre-Chinle erosion surface, and chiefly in the coarse-grained Shinarump and Moss Back rocks that filled the channels in that surface.

Chinle formation

The Chinle formation, which is of Late Triassic age, is widely distributed in northern Arizona, northwestern New Mexico, western Colorado, and Utah. The term "Chinle formation", as used in this report, covers not only the four lithologic subdivisions recognized by Gregory (1938), but also the underlying Shinarump conglomerate, which Gregory and others have described as a separate formation. The Shinarump, in other words, is to be regarded here as the oldest member of the Chinle._/

_/ See footnote p. 16

Two other units, also, are important to this report, both of them near the base of the Chinle, and each of them resting directly, in some places, upon the pre-Chinle erosion surface. Next younger than the Shinarump is the mudstone unit below the Moss Back, and the youngest of the three is the Moss Back member. The Moss Back, being coarse-grained like the Shinarump, has in the past been identified with it (Baker, 1933, 1935, and 1946, Gilluly, 1929, McKnight, 1940), but there is clear evidence, especially on Elk Ridge and in White Canyon, that the two are distinct. The rather unusual relations of these three units are shown in figure 4.

The overlying main body of the Chinle is not subdivided into members here but will be described as a whole.

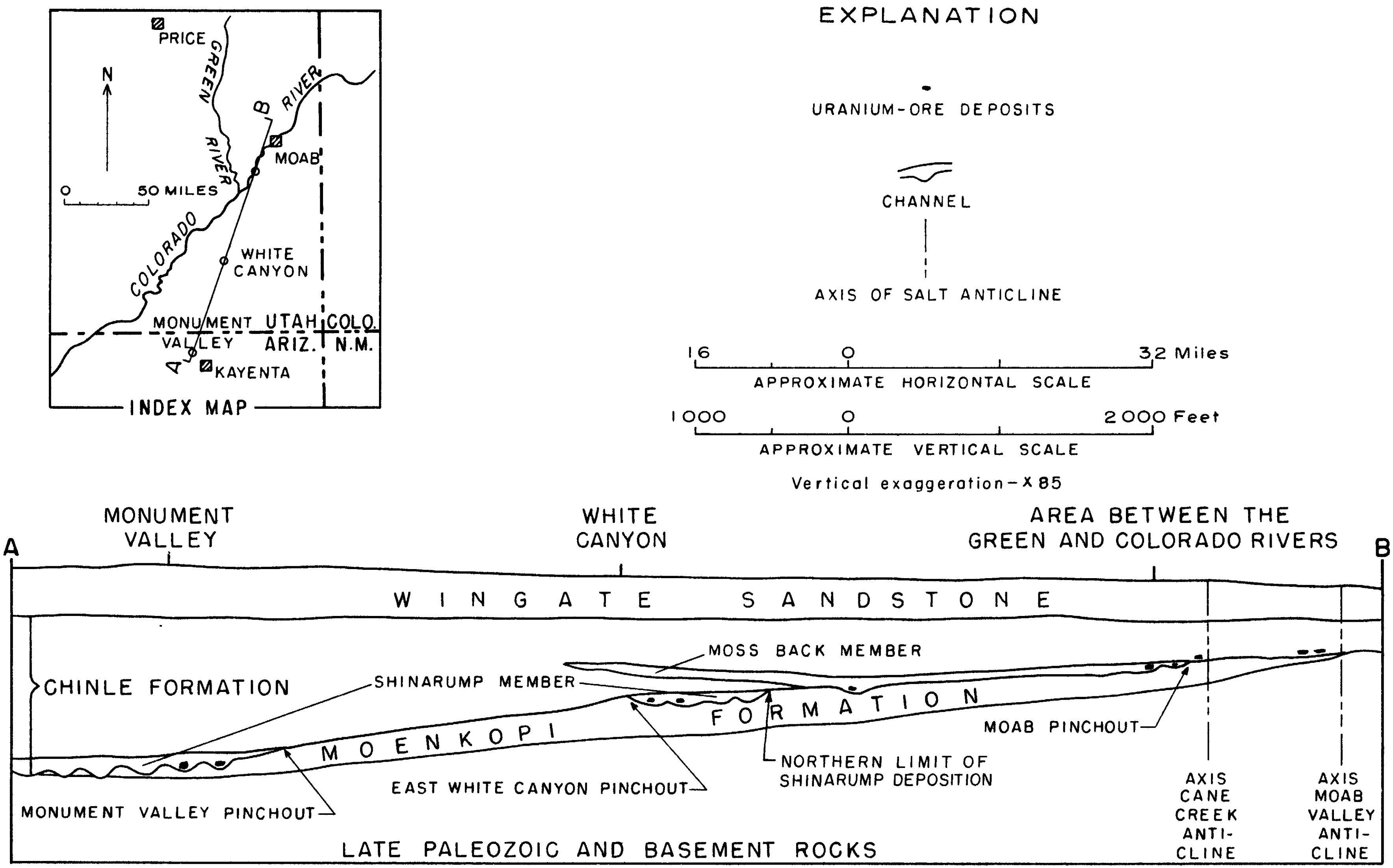

Figure 4. DIAGRAMMATIC CROSS-SECTION SHOWING THE RELATIONS OF URANIUM ORE DEPOSITS TO SOME STRATIGRAPHIC AND STRUCTURAL FEATURES OF THE MAIN TRIASSIC ORE-BEARING BEDS.

Figure 2 shows the outcrop pattern of only the main Triassic ore-bearing beds. These beds everywhere lie on or close to the mid-Triassic unconformity, but their stratigraphic position differs from place to place. The main Triassic ore-bearing bed in the south half of the area shown on figure 2 is the Shinarump member, whereas that in the north half of the area is the Moss Back member. In places where both the Shinarump and the Moss Back members are absent, only the mid-Triassic unconformity is shown on figure 2, which does not show the outcrop patterns of the Moenkopi, of the part of the Chinle above the Shinarump and Moss Back members, or of the Wingate.

Shinarump member.--The Shinarump member of the Chinle formation crops out in northern Arizona and part of southern Utah. The approximate northern limit of Shinarump deposition in southeastern Utah is near the north end of Elk Ridge and near the junction of the Dirty Devil and Colorado Rivers as shown in the center of figure 2. _/ According to

_/ Stewart, J. H., and others, in preparation, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, with a section on sedimentary petrology, by R. A. Cadigan: U. S. Geol. Survey Bull.

these writers, the limit is difficult to locate, as strata correlative to the Shinarump form thin, small scattered lenses near the northern limit, and detailed work may find lenses north of those now known. Furthermore, the northwestern extension of this northeastern limit is not known because of covered areas and of uncertainties of the relation of the Shinarump with similar small lenses of sandstone in the San Rafael Swell area.

A pinchout, in this report, refers to the edge of a formation, member, or ore-bearing unit beyond which it no longer forms a mappable unit. The nature of each pinchout varies; some beds end rather abruptly against a slope, either because of non-deposition or erosion; other beds become less continuous until they are totally absent. A special case of a pinchout is the northern limit of deposition of the Shinarump. The term "pinchout" is applied, generally, to those local edges of deposition within the main area of deposition. On figure 2 the very devious outcrops of the Shinarump along the cliffs and slopes can be followed, and can be seen to end at places marked by heavy lines, each designated by some such term as "Monument Valley pinchout." All the pinchout lines, including the northern limit of Shinarump deposition, on figure 2 are highly generalized, since the actual edges of the Shinarump are concealed and must be sinuous. Within the main area south and west of the approximate northern limit of Shinarump deposition, six distinct pinchouts of a regional nature are known. For purposes of discussion these pinchouts are called the Monument Valley, the East White Canyon, and West White Canyon, and the Circle Cliffs pinchouts, all shown on figure 2, and the Echo Cliffs and the House Rock Valley pinchouts, both west of Monument Valley (fig. 1).

The Monument Valley and East White Canyon pinchouts may be due to a slight topographic high caused by a structure ancestral to the Monument upwarp that controlled Shinarump deposition. In Monument Valley, streams that cut and filled the deep channel-scours flowed from the south and southeast _/ near the Monument Valley pinchout

_/ See footnote p. 19.

and roughly parallel to it (fig. 5), whereas, the streams that cut and filled the shallow channel-scours in White Canyon flowed from the east and northeast (See Stewart and others, footnote p. 19) along the East and West White Canyon pinchouts (fig. 5). If the courses of these streams were controlled by a topographic high nearly coextensive with the central part of the Monument upwarp, the Monument Valley and East White Canyon pinchouts may connect to form an oval-shaped area, inside which the Shinarump is absent. The northwest end of the Monument Valley pinchout line may be inferred to swing sharply to the north and connect with the south end of the East White Canyon pinchout line. Furthermore, the southeast end of the Monument Valley pinchout line may swing sharply to the north, parallel to but east of Comb Ridge, and may connect with the east end of the East White Canyon pinchout line.

In the Circle Cliffs area, the lithology of the Shinarump and the orientation of the deep channel-scours filled with Shinarump suggest that the Shinarump of the Circle Cliffs area is more directly related to the Shinarump in Monument Valley than that in White Canyon (fig. 5). The Shinarump pinches out along the eastern edge of the Circle Cliffs anticline. According to J. Fred Smith (oral communication), the Shinarump becomes very discontinuous in the east part of the Capitol Reef area, north of Circle Cliffs, and it may be near a pinchout. Thus, the Circle Cliffs pinchout may extend northward into the area just east of Capitol Reef (fig. 2).

The Echo Cliffs pinchout may be related to the Echo Cliffs monocline in the same way that the East White Canyon and Monument Valley pinchouts are related to the Monument upwarp; and the House Rock Valley pinchout may be similarly related to the East Kaibab monocline.

A sedimentary structure of special importance in the Shinarump is the channel, which, in this report, refers to the sedimentary unit consisting of a prominent linear scour and its filling of sedimentary rocks, most of which are dominantly coarse grained. Channels increase the thickness of the Shinarump downward. Some channels have relatively steep sides and rounded bottoms; others must be measured accurately to the nearest foot in order to define their sides, bottoms, and also, trend. Channels form as part of a continuous bed of normally even thickness or form long discontinuous lenses, like "shoestring sands." The depth of scour of a channel is measured from the bottom of the even-thick bed to the lowest point of the scour. The depth of scours differs from place to place: in the Monument Valley it is as great as 125 feet; in White Canyon it is commonly less than 15 feet; in the Circle Cliffs it is rarely less than 25 feet or more than 50 feet. The Shinarump is generally only 30 to 50 feet thick in the areas between channels and it attains a maximum thickness of about 225 feet in one channel in western Monument Valley. The width of the channels ranges from a few feet to more than a thousand feet in Monument Valley and from a few to several hundred feet in the White Canyon and Circle Cliffs areas. Channels in the Shinarump have been traced for many thousands of feet. The ends of some of them have been found in Monument Valley, and I. J. Witkind (1956, p. 235) has distinguished short channels from long channels. The channels in the Monument Valley, White Canyon, and Circle Cliffs areas make up about 3 percent of the area of the Shinarump blanket in those areas.

The Shinarump is conformable with the overlying members of the Chinle, and grades into them in many places.

The Shinarump member consists mainly of light-brown or light-gray sandstone and conglomeratic sandstone, and of subordinate amounts of conglomerate, siltstone, and mudstone. Conglomeratic strata, and also beds blocks, and pellets of mudstone are commoner near the bases and sides of channels than in the spaces between them. The pebbles in the conglomerate consist mainly of quartz and quartzite (78-98 percent of all pebbles), _/ but some of them consist of chert,

_/ See footnote p. 16.

silicified limestone, sandstone, or siltstone. The blocks and pellets of mudstone were probably derived from reworked Moenkopi, but the interstitial mudstone and the beds of mudstone may be partly from other sources. Most of the mudstone in the Shinarump is altered from red or brown to gray or green. The sand grains in the Shinarump consist mainly of quartz, feldspar, and mica; the immediate source of most of the mica is thought to be reworked Moenkopi. Fossil wood and other plant remains, either silicified or carbonized, are fairly common in the channels. Trash zones, which are composed of abundant irregularly distributed pebbles and carbonized plant fragments in a matrix of mudstone, are especially common in channels. Within channels, small scale scour-and-fill structures, cross-stratification, and graded and irregular bedding are the rule; outside the channels festoon-bedding and cross-stratification are most common.

Uranium, vanadium, and copper minerals are common in the Shinarump, but large ore-grade concentrations are limited to the channels, particularly to those near the pinchout.

Mudstone unit below the Moss Back.--The mudstone unit below the Moss Back, which is not given a formal name here, crops out only in part of eastern Utah. It forms the interval between the base of the Moss Back and the top of the Shinarump, or where the Shinarump is absent, the top of the mid-Triassic unconformity. Most geologists (A. F. Trites, Jr., T. L. Finnell, R. Q. Lewis, J. F. Smith, and others, all oral communications) do not give this unit a formal name, but Stewart_/ calls this unit the Monitor Butte member in the

_/ See footnote p. 16.

White Canyon area, the Capitol Reef area, and the southern half of the San Rafael Swell. He correlates this unit with the Monitor Butte member of Monument Valley. In the north half of the San Rafael Swell at least 2 divisions of the mudstone unit may be made. In this present report, the mudstone unit will not be divided and will be limited to areas where the Moss Back is present. New stratigraphic data may necessitate slight revisions of generalities presented here.

The mudstone unit is about 250 feet thick in White Canyon but it gradually thins northward until it pinches out along Indian Creek. In the San Rafael Swell it is generally less than 50 feet thick.

The mudstone unit consists mainly of gray and green mudstone and siltstone with scattered light-colored sandstone lenses, and it forms a slope below the Moss Back ledge. The sandstone lenses are lithologically similar to the Shinarump; and, where they lie on the mid-Triassic unconformity, they are generally correlated with and called Shinarump. Uranium deposits occur in the sandstone lenses in the mudstone unit north of White Canyon, particularly where they lie within 50 feet of the mid-Triassic unconformity, and one large ore deposit at the Hidden Splendor mine in the San Rafael Swell is in one of these lenses. _/

_/ See footnote p. 19.

Moss Back member.--The Moss Back member of the Chinle formation crops out in parts of eastern Utah and western Colorado, and it forms the main ore-bearing zone in the San Rafael Swell, area between the Colorado and Green Rivers, Lisbon Valley area, and Dolores River Valley area (fig. 2). Although the outcrop pattern shown in figure 2 for the Shinarump generally represents the northern limit of Shinarump deposition, the outcrop pattern for the Moss Back does not represent the southern limit of Moss Back deposition, because the Moss Back overlaps from south to north onto the Shinarump and the lower Chinle mudstone unit (fig. 4). The Moss Back crops out in White and Red Canyons, and on Elk Ridge, but is not shown there in figure 2 because of the small scale of the map.

The Moss Back, which was deposited by northwest-flowing streams _/

_/ See footnote p. 19.

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is a blanket-like deposit of fairly even thickness except where channels are locally abundant along its northern edge of deposition and in parts of the San Rafael Swell. Less than 1 percent of the total areal extent of this member consists of channels. McKnight (1940) noted that the Moss Back (which he called the Shinarump) pinched out along an irregular east-west line in the area between the Green and Colorado Rivers. This Moab pinchout, as it may be called, was probably due to several slight topographic highs along parts of the Cane Creek and Shafer salt anticlines, and it will probably be found to extend southeastward along the Lisbon Valley and Dolores Valley salt anticlines. The writer further thinks a northwestward-flowing drainage system developed along the Moab pinchout, for toward the northwest the channels become fewer in number and are farther apart. The Temple Mountain, Lucky Strike No. 2, and Dirty Devil deposits in the San Rafael Swell area are in channels that appear to belong to such a system (fig. 5). The channels range in width from a few tens of feet to several thousand feet, and some of them have been traced for many thousand feet along their length.

The Moss Back is very similar to the Shinarump, in that it consists mainly of light-brown or light-gray strata of sandstone and conglomeratic sandstone and subordinate amounts of conglomerate siltstone, and mudstone. The main lithologic difference _/ between

_/ See footnote p. 16.

the two consists in the character of their pebbles: in the Moss Back the pebbles are mainly of quartzite (43 to 48 percent) and chert (34 to 43 percent), whereas in the Shinarump they are mainly of quartz (78 to 96 percent). The sand in the Moss Back, moreover, is fine- to medium-grained, whereas that in the Shinarump is fine- to coarse-grained. These differences in kinds of pebbles and in grain size are so subtle and inconsistent that they cannot be used alone with complete success in distinguishing between the Shinarump and Moss Back in isolated outcrops or drill cores.

The Moss Back is overlain conformably by the upper part of the Chinle, and grades into it in many places. Its base generally rests on an erosion surface, in which there are channels as much as 50 feet deep. The Moss Back is generally 30 to 50 feet thick, and it attains a maximum thickness, including the channel, of about 150 feet.

Uranium, vanadium, and copper minerals occur in the Moss Back north of the White Canyon and Capitol Reef areas, and in some channels they are abundant enough to form ores.

Main body of Chinle.--The main body of the Chinle crops out in most parts of the Colorado Plateau, and it generally forms a steep slope above narrow benches of Shinarump or Moss Back. Division of the main body of Chinle cannot be summarized briefly because the members are different from one area to another, because regional stratigraphic studies of the Chinle are still in progress, and finally, because the subdividion of the main body of Chinle is not pertinent to the present discussion.

The contact of the Chinle with the overlying Wingate is generally conformable. The thickness of the main body of the Chinle ranges from a maximum of nearly 1,500 feet in Arizona to zero where it pinches out against the Uncompaghre Plateau in Colorado.

The main body of the Chinle consists chiefly of red, gray, purple, and green mudstone, claystone, and siltstone and subordinately of gray sandstone, conglomerate, and limestone, which form persistent ledges in some places. A large amount of bentonite occurs in the silty and muddy parts of the Chinle in eastern Utah and northern Arizona, whereas bentonite is notably absent in the Chinle in western Colorado (R. A. Cadigan, oral communication). Fossil wood and other plant remains, some of them silicified and others carbonized, are common.

Uranium, vanadium, and copper minerals are found in the lower parts of the main body of the Chinle but seldom in the upper parts. Ore deposits are concentrated in siltstone and sandstone beds at the base of the main Chinle body, incidentally on or near the mid-Triassic unconformity, in the area north of the Moab pinchout and in siltstone and poorly consolidated sandstone beds in the lower hundred feet of main Chinle body in the Cameron-Holbrook area.

Wingate sandstone

The Wingate sandstone crops out in most parts of the Colorado Plateau. It is of Late Triassic age and is generally conformable with the underlying Chinle and the overlying Jurassic(?) Kayenta formation. It ranges from a maximum thickness of 500 feet in Arizona to zero thickness in Colorado where it pinches out locally against the Uncompahgre Plateau, but it is most always between 250 and 400 feet thick.

Most of the Wingate consists of yellowish-gray to red fine-grained sandstone, mainly composed of quartz grains that appear megascopically to be of nearly uniform size. In places, however, it contains many beds of red mudstone near the base. The sandstone is commonly cross-bedded, but the bedding is seldom clearly visible even on the characteristic sheer massive cliffs, because these are largely coated with black "desert varnish."

Uranium, vanadium, and copper minerals occur in fracture or shear zones in the Wingate at some widely separated localities, but seldom are the minerals concentrated into significant ore-grade bodies.

Igneous rocks

Igneous rocks of latest Cretaceous or early Tertiary age, forming stocks, laccoliths, plugs, dikes, sills, and flows, are widely but sparsely distributed on the Colorado Plateau. The well-known Henry, Abajo, and La Sal Mountains (fig. 2), which are stocklike centers flanked by laccoliths, are in eastern Utah, and there are similar laccolithic mountains in Arizona and Colorado but farther to the south and east. Plugs, dikes, and diatremes (diatremes being funnel-shaped vents filled chiefly with tuff and formed by escaping volcanic gases) occur mainly in northeastern Arizona and northwestern New Mexico, and flows are most common along the periphery of the Colorado Plateau region.

The intrusive rocks in the laccolithic mountains are mainly diorite porphyry and monzonite porphyry but include minor amounts of aplite and syenite. The plugs and dikes consist mainly of minette and monchiquite, and the flows mainly of basalt. The diatremes contain a wide variety of materials: the upper part of a fully developed diatreme is filled with bedded tuff, limestone, and fine-grained clastic rocks, but lower down these sediments give way to massive tuff, breccia, blocks of country rock, agglomerate, and finally to solid igneous rock (Shoemaker, 1956).

Structure

The main structural features of the Colorado Plateau are of two classes: (1) deep-seated structures, caused by deformation in the basement rocks, and (2) shallow structures, caused by intrusion of halite, gypsum, and near-surface laccoliths into the sedimentary rocks_/.

_/ Luedke, R. G., and Shoemaker, E. M. 1953, Tectonic map of the Colorado Plateau: U. S. Geol. Survey open-file map, and short text.

The deep-seated structures include extensive monoclines, large domes around the stocks in the centers of laccolithic mountains, small structures related to volcanic plugs, and also calderas and explosion vents. The shallow structures, on the other hand, include laccolithic anticlines and salt anticlines. All these structures are commonly accompanied by extensive faults and joints.

Large monoclines occur mainly along the east and west sides of the Colorado Plateau region. In general, those on the east side dip westward and those on the west side dip eastward. The large domes around the stock centers of the laccoliths have no apparent relation to other major structures. Small laccolithic anticlines occur about the stocks of these domes.

Near the La Sal Mountains, in eastern Utah and western Colorado, northwest-trending anticlines have been formed by the intrusion of salt, gypsum, and the soft shale of the Paradox member of the Hermosa formation, which is of Pennsylvanian age. These salt anticlines were formed in Permian time but continued to rise until Late Jurassic time.

R. G. Luedke and E. M. Shoemaker _/ indicate the probable sequence

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_/ See footnote above.

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of Cenozoic structural events as follows:

"1. Pre-Eocene monoclinal folding on the west side of the Plateau.

2. Anticlinal folding in the salt plug region, possibly contemporaneous with monoclinal folding on the east side of the Plateau.

3. Normal faulting in the central part of the Plateau, along northwest trends contiguous with the salt anticlines.

4. Injection of stocks and laccoliths...

5. Late Tertiary vulcanism and faulting on the borders of the Colorado Plateau, and epirogenic uplift of the entire Plateau.

6. Renewed uplift and faulting during the Pleistocene, as along the Uncompahgre uplift. Excavation of valleys along the salt anticlines, accompanied by faulting along the crests and flanks of the anticlines."

ORE DEPOSITS

Classification

The ore deposits in the sedimentary rocks of the Colorado Plateau contain uranium, vanadium, and copper in widely differing amounts. All gradations are known between deposits valuable for one of these metals to deposits valuable for two of them. Many vanadium deposits that contain little if any uranium or copper occur in the Entrada sandstone of Jurassic age in western Colorado. Copper deposits that contain little if any uranium or vanadium occur in the Shinarump conglomerate in White Canyon, Utah, in the Burro Canyon formation in Big Indian Wash, Utah, and in the Navajo sandstone in Arizona (Finch, 1955).

The uranium ores in Triassic rocks generally contain more vanadium or copper than uranium. They may be classified according to the relative abundance of these metals, as vanadium-uranium, copper-uranium, and uranium (vanadium and copper minor) deposits.

 (page 35 follows)

Production or assay data (where values are given as percent of V_2O_5, of U_3O_8, and of Cu) give the best means of assigning a deposit to one of these three types. A deposit may contain local concentrations of minor constituents such as copper or vanadium, or more rarely of cobalt, molybdenum, or lead, but it is classified only by naming the metal or metals for the sake of which it is mined.

The habits of the ore in all three classes of deposits are similar and are independent of the host formation; ore minerals occur as impregnations and replacements largely of sandstone and conglomerate. Most of the ore bodies form irregular layers or concretions although many fossil logs have been found that have been partly replaced by uranium minerals. The margins of ore bodies may be either sharp or gradational into unmineralized or only slightly mineralized rock and the upper and lower margins are conformable to the bedding planes of the host rock; such deposits are loosely termed "bedded deposits." A very few deposits are localized in shear zones and fractures and have some of the characteristics of veins. The "bedded deposits" are in the Chinle and Moenkopi formations, whereas the vein-like deposits are mostly in the Wingate sandstone.

Vanadium-uranium deposits

In the vanadium-uranium deposits the ratio of vanadium (V_2O_5) to uranium (U_3O_8) ranges from 1:1 to 10:1. In some large mines, such as the Monument No. 2 mine in Monument Valley, Arizona, the Temple Mountain mines in Emery County, Utah, and the Mi Vida mine in Big Indian Wash, Utah, the ratio is near 3:1 (fig. 7), whereas the lowest ratio in most of the deposits in the Morrison formation in the Uravan mineral belt is about 5:1 (Fischer and Hilpert, 1952).

The unoxidized vanadium-uranium deposits, which are termed "black ores" (Weeks and Thompson, 1954), commonly contain uraninite, montroseite, and doloresite, associated with sulfides of iron, copper, and lead. Such ores occur in parts of the Monument No. 2 and the Mi Vida mines.

In the oxidized vanadium-uranium deposits, generally called "carnotite deposits" on the Plateau, the common ore minerals are carnotite, tyuyamunite, vanadium hydromica, and hewettite, commonly associated with limonite and hematite. Such deposits occur, for example, in the belt that extends from the Monument No. 2 mine to the Whirlwind mine in Monument Valley, and also in the Temple Mountain and Big Indian Wash areas.

Copper-uranium deposits

In copper-uranium deposits the ratio of copper (Cu) to uranium (U_3O_8) ranges from 1:1 to 18:1 and vanadium is almost absent. In the largest deposits of this class the copper-uranium ratio is commonly low; in the Happy Jack deposit in White Canyon, San Juan County, Utah, it is about 3:1.

The unoxidized portions of copper-uranium deposits consist mainly of uraninite associated with iron and copper sulfides, the most abundant being pyrite, chalcocite, covellite, and bornite. In many places, uraninite and sulfides have replaced wood. Unoxidized copper-uranium ores occur in parts of the Happy Jack and Yellow John mines in White Canyon. The oxidized portions of copper-uranium deposits consist mainly of torbernite, betazippeite, uranopilite, and johannite.

Mine faces cut in unoxidized ore, when exposed for a short time, become covered with an efflorescence of these bright-colored minerals. The Happy Jack and Yellow John ore bodies have a narrow zone of oxidation near their surface outcrop.

Uranium (vanadium and copper minor) deposits

These deposits classed as uranium (vanadium and copper minor) contain ore-grade amounts of uranium and only minor amounts of vanadium or copper. The unoxidized ores in them consist mainly of uraninite but contain minor amounts of iron and copper sulfides. Such ores form parts of the deposit at the Hidden Splendor mine, in the San Rafael Swell in Emery County, Utah, and of many deposits in the area between the Green and Colorado Rivers.

Uranium deposits of this class are remarkably free from oxidation, as a rule, even near the surface, and commonly escape detection, because of their lack of colorful secondary minerals. In places where they are oxidized their secondary minerals are mainly becquerelite and schroeckingerite. Oxidized uranium (vanadium and copper minor) ores occur in the Hidden Splendor mine, and also in some of the mines between the Green and Colorado Rivers.

Mineralogy

Although the mineralogy of the ore deposits is complex and differs from place to place, certain ore and associated non-ore minerals are by far the most abundant. The unoxidized ore minerals consist mainly of oxides and sulfides, but the oxidized ore minerals have a great range in composition. Iron minerals form the bulk of the non-ore minerals in the ore. Weeks and Thompson (1954) discuss the uranium and vanadium minerals of the Colorado Plateau in detail.

Principal uranium minerals

Uraninite (pitchblende), which is ideally UO_2 but commonly contains UO_3, is a common and rather abundant mineral in the unoxidized parts of the deposits. It occurs chiefly with sulfides, especially pyrite, chalcocite, and covellite, and with carbonaceous material. Some of it is intimately mixed with sulfides, some replaces carbonaceous material and parts of the host rock. Some impregnates sandstone, and some has completely replaced the enclosing rock to form solid masses several inches across. In polished section the uraninite from these deposits is massive, and rarely if ever botryoidal or spherulitic like that of the pitchblende veins described by Everhart and Wright (1953).

A new mineral named coffinite $[U(SiO_4)_{1-x}(OH)_{4x}]$ is probably more common and abundant than is generally realized (Stieff, Stern, and Sherwood, 1955). It occurs with uraninite, which it resembles in associations and forms.

The kinds of uranium minerals contained in oxidized ore deposits depend upon what other elements are present, especially vanadium and copper; they include hydrous oxides, carbonates, sulfates, phosphates, arsenates, vanadates, and silicates. Garrels (1955) discusses the thermodynamic relations among the uranium oxides and their relation to the oxidation states in the uranium ores. Uraninite commonly oxidizes to form becquerelite ($2UO_3.3H_2O$). The most abundant oxidized vanadium-uranium minerals are carnotite and tyuyamunite, the potassium and calcium uranyl vanadates. The most abundant oxidized copper-uranium minerals are torbernite ($Cu(UO_2)_2(PO_4)_2.8\text{-}12H_2O$) and johannite ($Cu(UO_2)_2(SO_4)_2(OH)_2.6H_2O$). Commonly associated with these are betazippeite $(UO_2)_2(SO_4)(OH)_2.4H_2O$) and uranopilite $(UO_2)_6(SO_4)(OH)_{10}.12H_2O$).

Principal vanadium minerals

Vanadium minerals found in deposits in the Triassic rocks are various oxides and hydrous oxides whose thermodynamic relations have been discussed by Garrels (1953). The unoxidized vanadium minerals are an unnamed vanadium mineral (probably valences $V+3$ and $V+4$, hydrated) (Weeks and Thompson, 1954) and montroseite, ($VO(OH)$ or $(V,Fe)O(OH)$ (Weeks, Cisney, and Sherwood, 1953).

The chief oxidized vanadium minerals are roscoelite ($(Al, V)_2(AlSi_3)(K,Na)O_{10}(OH,F)_2$), vanadium hydromica, which contains less potassium and more water than roscoelite, and corvusite ($V_2O_4.6V_2O_5.nH_2O$?). Hewettite ($CaV_6O_{16}.3\text{-}9H_2O$) is also common in some oxidized vanadium-uranium deposits, where it occurs as coatings on fractures and as fracture fillings.

Principal copper minerals

The common unoxidized copper minerals in deposits in Triassic rocks are chalcopyrite, chalcocite, covellite, and bornite. These minerals occur in both uraniferous and nonuraniferous rock; in some places they replace either wood or host rock, and in others they are intermixed with uraninite and pyrite. Chalcocite commonly occurs as small, a quarter of an inch or more across, round concretion like impregnations in sandstone. Preliminary microscopic study of the ores indicates a very close paragenetic relationship between copper sulfides and uraninite (Finch, 1954).

Of the oxidized copper minerals, by far the commonest is malachite. Others are azurite, chalcanthite, chrysocolla, and brochantite; and volborthite ($Cu_3(VO_4)_2 \cdot 3H_2O$?) occurs in deposits in the Wingate sandstone at Temple Mountain and in House Rock Valley and Richardson Basin, all in Utah.

Minerals associated with the ores

The valueless minerals associated with the ores are greatly varied in composition. Many of them are syngenetic rather than introduced. Oxides of iron and manganese are widespread and abundant; nearly all the oxidized deposits contain limonite, hematite, or jarosite. Pyrite or marcasite, or both, are common and in places abundant; they are generally associated with carbonaceous material, and commonly replace the cellular structure of plant remains. Galena has been observed in many deposits. Cobalt bloom (erythrite?) seems to occur mostly in large deposits.

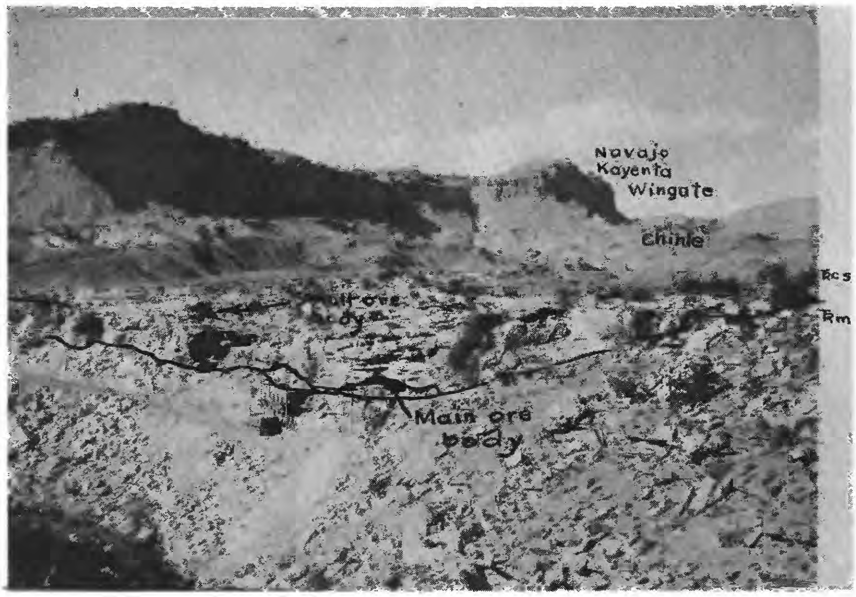
Common rock-forming minerals in the ores, other than quartz and detrital minerals, are calcite, gypsum, and clay. Calcite is found along fractures and bedding planes, and in the cement of sandstone. Gypsum is common and in places abundant in oxidized outcrops. An interstitial white clayey material, which may represent altered volcanic ash, is very common.

Carbonaceous material, much of it coal-like, is found in most deposits. In the San Rafael Swell and locally in other places, the ore-bearing beds contain carbonaceous material that has been called asphaltite by some and thucholite by others. Its chemical composition, however, indicates that this material is neither asphaltite nor thucholite (I. A. Breger, oral communication). Because of its possible genetic relationship with the uranium ore, its origin has been a subject of much research and study. The deposits at Temple Mountain in the Swell contain rare but perhaps significant minerals; these include realgar, native sulfur, sphalerite, and fairly abundant selenium.

Habits of ore deposits

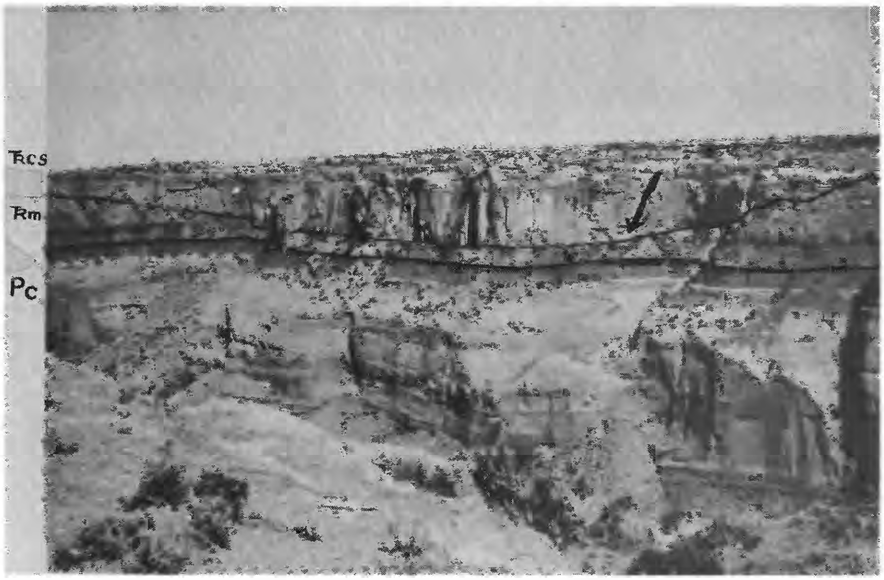
Minerals of uranium, vanadium, and copper are sparsely disseminated in much of the lower part of the Chinle formation; as much as 20 percent of the outcrop length of the main ore-bearing beds is mineralized in some areas. Ore deposits, however, each of which is commonly composed of many small ore bodies, have a rather spotty distribution. They occur most commonly near the bottoms of channels, (fig. 6), but there are small ore bodies in the upper and

FIGURE 6.--Photographs of typical ore-bearing and barren channels of the Shinarump member of the Chinle formation. Location of channels is shown on figure 5.



a) View looking northeast at the Posey channel, Red Canyon, San Juan County, Utah. The heterogeneous composition of this and channel b is typical of ore-bearing channels. The main ore body is near the bottom of the channel, but small ore bodies are in the upper part of the channel as shown by the partly mined body left of center. The mudstones of the Chinle overlying the Shinarump (TRcs) form a slope. Note the absence of the Moss Back member of the Chinle. A typical Wingate cliff, Kayenta bench, and Navajo cliff are in the background.

FIGURE 6.--Continued. b) View looking west at the Mitchell Mesa No. 1 channel, Monument Valley, Navajo County, Arizona. Small long concretionary ore bodies of the kind that are common in the Monument No. 2 mine occur near the bottom of this channel.



c) View looking southeast at the Alfred Miles No. 1 channel, Monument Valley, Navajo County, Arizona. The homogeneity of the rocks filling this essentially barren channel typifies unfavorable channels in the Shinarump. Minor efflorescence of copper, iron, and uranium minerals on the outcrop occurs at the point of the arrow in the photograph.

middle parts of some channels. Ore deposits are in general most abundant near beds of clay and mudstone, and commonly lie directly along their strike or immediately above or below them. Some ore bodies are in sandstone beds truncated by small scours filled with mudstone or by slump blocks of mudstone. Ore-bearing channels are heterogeneous, that is, they are filled with much fine-grained material as well as coarse-grained material. They can be easily recognized because they weather to form irregular, rough faces (Photograph A, fig. 6). Not all heterogeneous channels are known to contain ore, but they are more favorable for finding ore than homogeneous ones. Barren channels are most commonly homogeneous, are filled with clean sandstone, and may be recognized because they weather to form smooth, massive, nearly vertical faces (Photograph C, fig. 6).

Although the ore deposits occur in various kinds of rock and vary considerably in shape, size, composition, and grade, they have many characteristics in common.

The ore deposits are irregular in plan but are generally elongate and parallel or subparallel to the channel or lens in which they occur. Individual ore bodies generally follow such features as bedding, fossil logs, or especially permeable zones. The top and bottom boundaries of individual ore bodies conform to the bedding, except in detail, where they cut the bedding at low angles. Edges of ore bodies, on the other hand, commonly cut sharply across the bedding, particularly in the vicinity of logs, concretions, and small rolls. Assay walls are also common in many deposits. Some bodies form elongate lenses that are analogous to ore shoots with preferred orientation; such bodies occur at the Shinarump No. 1 mine in the Seven Mile Canyon area, Grand County, Utah (Finch, 1954), and at the Happy Jack mine in White Canyon (Trites and Chew, 1955). Many ore bodies are tabular or blanketlike; in the Mi Vide mine on Big Indian Wash, San Juan County, there are several such bodies, interbedded with nearly barren rock.

For the most part the ore minerals impregnate and are disseminated in sandstone, mudstone, or siltstone, but to a less extent they are richly concentrated along bedding planes and in logs, "trash" accumulations, nodules, and concretions. Although uranium minerals are disseminated in all types of sediments in the Triassic, including siltstone, mudstone, and limestone-pebble conglomerate, they tend to be concentrated in coarse-grained or poorly sorted parts of a rock, both on a megascopic and microscopic scale. The rock impregnated and disseminated with ore minerals, which makes up the bulk of the ore, is sharply delimited, as a rule, from barren rock. "Rolls" of the size and type commonly found in the deposits in the Morrison formation (Fischer, 1942, opposite p. 382, pls. 55 and 56) have not been observed by me in the deposits in the Triassic formations. Ore minerals richly concentrated in tubular concretionary bodies called "logs" by the miners, occur in many mines, including the Monument No. 2 mine, Apache County, Ariz., and the Mi Vida mine, San Juan County, Utah. The unoxidized minerals in the logs are mainly uraninite, montroseite, and pyrite; the oxidized minerals are carnotite or tyuyamunite and iron oxides. Many of the "logs" are clearly formed by replacement of wood, but others contain no wood, cut across bedding, and replace the host rock. Trash accumulations containing both carbonaceous material and mudstone are commonly rich in uranium minerals. Although carbonaceous material is associated with most of the ore deposits, not all of it, or even of that within or near ore deposits, contains uranium.

Not only the clay masses in the trash but some scattered clay pebbles, commonly have rims or inner zones impregnated with vanadium and uranium minerals. Where ore minerals are richly concentrated along bedding planes, it is apparently because they have impregnated or replaced thin films of clay or carbonaceous material.

High-grade ore in the form of nodules, replaced wood fragments and limestone pebbles, occurs in siltstone and limestone-pebble conglomerate beds in the lower part of the Chinle between the Green and Colorado Rivers. Rock containing the high-grade nodules in sufficient abundance can be mined as it is at the Shinarump No. 3 mine, Grand County, Utah (Finch, 1953).

Unoxidized uranium minerals are rare in large fractures or joints. _/ At Temple Mountain, some asphaltic ore possibly containing

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_/ Since this study was completed and report was written, a vein uranium deposit was discovered about 8 miles southwest of Moab, Utah, along the Colorado River. It occurs in a steeply dipping, east-trending fault, and ore-grade material is found in the Chinle, Moenkopi, and Rico formations. Wright, R. J., 1955. Ore controls in sandstone uranium deposits: Econ. Geology, v. 50, no. 2, p. 146.

uraninite, fills open fractures and faults in the Moss Back. It appears to me that these asphaltic ores were formed by the redistribution of "bedded" ore. T. L. Finnell (oral communication) has observed uraninite in microscopic fractures of quartz grains from the Monument No. 2 mine and in small weak fractures in sandstone from the Hideout mine, San Juan County, Utah. Oxidized uranium minerals commonly do fill fractures and joints near the surface, and chalcocite fills minute vertical fractures in ore-bearing siltstone at the Shinarump No. 1 mine.

Individual ore bodies differ widely in size and grade, even within a small area. A deposit may contain less than a ton of ore or several hundred thousand tons. The average thickness of individual deposits ranges from about 5 to 12 feet; the maximum thickness is rarely more than 30 feet, and the minimum thickness mined is about 2 feet. Thin layers of high-grade uranium ore account for little tonnage. Minable uranium ore contains from 0.10 percent to more than 1.00 percent U_3O_8, and vanadium-uranium ores contain from 0.20 percent to more than 3.00 percent V_2O_5. In copper-uranium deposits the percentage of copper also is about 0.20 to 3.00. Rock that contains from 0.02 percent to 0.10 percent U_3O_8 forms low-grade halos around some of the deposits and also forms separate deposits in some areas. The lime content (acid solubles, mostly calcium carbonate) of the ore differs widely from place to place, but rarely exceeds 6 percent (maximum percent allowable without incurring a penalty) except at some mines in the Big Indian Wash area and in the area between the Green and Colorado Rivers.

Wall-rock alteration of the type commonly associated with hypogene metalliferous deposits is not found in these ore deposits. Ore-bearing rocks, however, have commonly been altered from red to gray and green throughout eastern Utah and northeastern Arizona. That is particularly true of mudstone in and beneath the ore-bearing beds, but the relation between ore and altered mudstone is not so close in the Triassic formations as it is in the Morrison formation (Weir, 1952). Ore-bearing sandstone in many deposits is heavily iron-stained and commonly in bands like Liesegang rings, or is silicified. Zoning is common in the oxidized parts of deposits; in the Yellow John mine, for example, the rock surrounding the ore bodies is banded with secondary copper minerals and hematite and limonite.

DISTRIBUTION OF ORE DEPOSITS

Uranium deposits in Triassic rocks are distributed over an area of about 100,000 square miles in Utah, western Colorado, and northern Arizona (figs. 1 and 2). In a reconnaissance study of nearly 400 mines and prospects in this area, mere uneconomic occurrences of uranium minerals have been distinguished from the significant ore deposits, which are considered in this report to be those that have produced, or have in reserve, several hundred tons or more of ore, or that appear likely to contain such quantities of ore. In order to delineate broad areas likely to contain significant deposits hitherto undiscovered, the geologic relations and geographic distribution of those already known have been studied.

Most of the significant deposits are in the Chinle formation. The Moss Back member of the Chinle appears to be a more important source of uranium than the Shinarump member, and ore deposits are most likely to occur in channels that lie less than 50 feet above the mid-Triassic unconformity._/ The main guides to ore and favorable

_/ See footnote 19.

ground are channels and abundant carbonaceous material and mudstone. The deposits in the Moenkopi and Wingate formations are widely scattered and mostly small.

From these data it appears that significant deposits are most likely to be found in three elongate areas or belts underlain by the Triassic rocks that contain most of the known deposits. These are, from south to north, the Monument Valley belt, the East White Canyon belt, and the Moab belt (fig. 7), all of which follow, for the most part, channel systems near the pinchouts of the Shinarump or the Moss Back. Other areas, whose boundaries were not defined, are underlain by Triassic rocks and appear likely to contain significant deposits; the most promising are the western part of White Canyon, the Circle Cliffs, and the area along the Little Colorado River.

Monument Valley belt

The Monument Valley belt of favorable ground is an area about 8 miles wide and over 40 miles long, convex toward the south, that extends from the Monument No. 2 mine on the east to the Whirlwind mine on the west (fig. 7). The east end of the belt may turn southward about parallel to the crest-line of the Comb Ridge monocline, and its west end may connect with the west end of the East White Canyon belt. The boundaries of the Monument Valley belt are drawn on the basis of the geologic guides to ore outlined below. The northern boundary nearly coincides with the Monument Valley pinchout, whereas the southern boundary is based principally upon the change from heterogeneous material filling the channels inside the belt to more homogeneous material filling the channels outside the belt (fig. 5).

The significant deposits in the Monument Valley belt which are all in the Shinarump have a spotty distribution. They are all of the vanadium-uranium type, whereas the small showings outside the belt but near it are of the copper-uranium type. In the western part of Monument Valley but outside the belt of favorable ground, there are extremely large channels that contain small showings of oxidized uranium and copper minerals formed by evaporation of present-day circulating ground water (Photograph c, fig. 6). These minerals were derived either from traces of uranium and copper in the Shinarump or from buried ore deposits.

Geologic guides to favorable ground and significant ore deposits in Monument Valley, in order of importance, are: 1) channels near the pinchout of Shinarump conglomerate; 2) sandstone and conglomerate containing abundant carbonaceous material and interbedded mudstone, near the bottoms of channels (fig. 6); and 3) presence of secondary vanadium minerals. Alteration of mudstone in the Shinarump and the underlying Moenkopi is too widespread in Monument Valley to be useful as an ore guide. I. J. Witkind, R. E. Thaden, and C. F. Lough, in an unpublished report (1953) have listed guides to prospecting in the Arizona part of Monument Valley as follows: 1) "paleochannels," 2) organic matter, and 3) "paleochannel conglomerates" containing organic matter. Other possible guides that they have listed but regarded as of uncertain value are: 1) limonite impregnation, 2) copper minerals, 3) bleached zones in the Moenkopi, and 4) boulders, cobbles, and pebbles of clay. With the exception of the presence of limonite and copper, which did not seem particularly significant, the guides suggested in the present report agree in essentials with those listed by Witkind, Thaden, and Lough. They, and Witkind in a later report (1954) do not recognize the pinchout as a guide to ore; they believe that all channels are favorable for ore regardless of their location. Witkind and his fellow workers, however, limited their study and conclusions only to the Arizona part of Monument Valley.

East White Canyon belt

The East White Canyon belt of favorable ground is from 2 to 8 miles wide and 30 miles long (fig. 7). Its eastern end is probably at the base of the Abajo Mountains, and its western end may connect with the Monument Valley belt. Its southern boundary coincides with the East White Canyon pinchout; its northern boundary delimits the belt from an area in which the channels are smaller and less continuous than those within the belt.

In the lower part of White Canyon there are small areas of favorable ground near the Happy Jack and Jomac mines. These areas are not easily defined, but they are all near the West White Canyon pinchout (A. F. Trites, Jr., and others, written communication) and another belt may extend along this pinchout. The Happy Jack and Jomac deposits are in channels that may be part of the channel system in the East White Canyon belt.

The significant deposits in the White Canyon belt are irregularly scattered in the Shinarump. They are all of the copper-uranium type. On Elk Ridge, a small deposit associated with asphaltic(?) material occurs in the Moenkopi, about 50 feet below the Moenkopi-Shinarump contact (fig. 7).

Geologic guides to favorable ground and significant ore deposits in the White Canyon area are in order of importance: 1) channels, especially those near the pinchouts of the Shinarump, 2) abundant carbonaceous material and interbedded mudstone, and 3) presence of copper sulfides, especially covellite and chalcocite.

Benson and others (1952) say that the ore controls (guides?) are "ancient channel fills," fractures, carbonaceous material, and clay, but fractures did not appear to me to be particularly significant as guides to ore in the White Canyon area.

Moab belt

The Moab belt, which is from 10 to 20 miles wide and over 130 miles long, includes 1) the southern part of the San Rafael Swell, 2) a part of the area between the Green and Colorado Rivers, 3) the

Big Indian Wash area, and 4) the Dolores River Canyon area (fig. 7). It is characterized by an alinement of significant deposits and areas of geologically favorable ground, but it is not as well defined as the Monument Valley and East White Canyon belts, and contains some patches of unfavorable ground. The northern boundary of the Moab belt is based mainly on the extent of the channel systems along the flanks of the Moab Valley and Lisbon Valley anticlines, and on changes in alteration and lithology in the San Rafael Swell. The southern boundary is based on channel systems near the edge of the Moab pinchout and other geologic guides described below and is projected to the south end of the San Rafael Swell. The existence of the Moab belt was first conceived early in 1952, and was at least in part substantiated early in 1953, by the discovery of a group of large deposits in the Big Indian Wash area.

The significant deposits in the Triassic of the Moab belt occur mainly in the Moss Back, but one of them at the Hidden Splendor mine is in a sandstone lens in the mudstone unit below the Moss Back, and others are in siltstone and sandstone beds in the lower part of the Chinle and in the Wingate. The deposits in the Moss Back have a spotty distribution; and, in some places, including parts of the Temple Mountain and Big Indian Wash areas they are clustered into groups.

Most of the deposits in the Moab belt contain vanadium and a minor amount of copper, but they include some vanadium-uranium deposits, mainly at Temple Mountain and in parts of Big Indian Wash and Dolores River Canyon areas. In three out of four of the large deposits in the Moab belt, the $V_2O_5:U_3O_8$ ratio is about 3 to 1, which is close to the minimum for the deposits in the Uravan mineral belt (fig. 7). Uranium predominates, however, in most of the other deposits, particularly in parts of the San Rafael Swell and in the area between the Green and Colorado Rivers.

Geologic guides to favorable ground and significant ore deposits in the Chinle of the Moab belt, especially in the Moss Back member, are roughly in order of importance: 1) channels or lenses, particularly near the Moab pinchout; 2) thinning or possibly pinching out of the Moss Back near the axes of salt anticlines; 3) abundant carbonaceous material, particularly asphaltlike material in the San Rafael Swell; 4) altered Moenkopi beds beneath channels, especially applicable in the area between the Green and Colorado Rivers; and 5) presence of chalcocite, bornite, and other copper sulfides, which occur mainly in the area between the Green and Colorado Rivers.

A guide of uncertain importance in the Moab belt is a purplish-white color band which crops out mainly in that belt, though it also crops out in a large area north of the belt in the San Rafael Swell and spotty occurrences of similarly colored rock were observed in parts of White Canyon and Monument Valley (fig. 5). The purplish-white band which generally occurs in the lower part of the Chinle or the upper part of the Moenkopi formations, is from 3 to 50 feet in thickness and generally forms a steep rubble-covered slope. Uranium deposits occur in beds that lie from a few feet to several tens of feet above it, and in the area between the Green and Colorado Rivers the band itself contains a few low-grade uranium-bearing deposits.

The purplish-white band is not everywhere a lithologic unit; in some places it consists of discontinuous altered and indurated zones in rocks of many types, all of them generally cemented with hematite. These rocks contain much limonite, gypsum, and calcite and are locally silicified, particularly where the band has been brecciated.

The purplish-white band is most likely a fossil soil zone developed in Triassic time(G. M. Richmond, oral communication). No genetic relationship between the purplish-white band and the uranium deposits can be proved, but their relation in space is pointed out to stimulate further study of this unusual phenomenon.

At Temple Mountain, in the San Rafael Swell, several small asphaltic deposits occur in the Wingate, about 200 feet stratigraphically above significant deposits in the Moss Back. These Wingate deposits are in or near a collapse feature complicated by land slides, which is called the "flopover" (Hess, 1922); they occur mainly along curved fractures, and along bedding planes intersected by mineralized fractures, in light-colored fine-grained sandstone. One prospect exposes a "roll" at the intersection of a fracture and a bedding plane resembling those common in the Morrison formation near Uravan, Colo., (Fischer, 1942). In the Richardson Basin area similar, but non-asphaltic, deposits occur in the Wingate sandstone, and outside the Moab belt   the Wingate contains similar but non-asphaltic deposits in House Rock Valley, Kane County, Utah (fig. 1), and Gypsum Valley, San Miguel County, Colo.

These deposits in the Wingate appear to have been deposited by ground water or hot-spring water that leached uranium from other nearby formations, and they may thus be important clues to other deposits in underlying rocks, as at Temple Mountain, or in overlying rocks, as in Gypsum Valley. The undiscovered deposits may be quite distant from these Wingate deposits, as they may be in House Rock Valley, and a careful search may be required to find them.

Uranium deposits occur in the Morrison formation within or near the Moab belt, but their distribution shows no significant relation to that belt. They are near the intersection of the eastern end of the Moab belt with the Uravan mineral belt (fig. 7), whose limits are defined by the distribution of deposits in the Morrison formation and by a change in the lithologic character of the ore-bearing beds north and east of the belt. As the localization of the deposits in the Morrison and in the Chinle are related to differently trending sedimentary features, the two belts are probably independent of each other.

Favorableness of other areas

South and west of the three favorable belts described above, the Triassic ore-bearing beds crop out in the Circle Cliffs, in Capitol Reef, in Happy, Hatch, and Poison Spring Canyons (fig. 7), in the vicinity of the Little Colorado River, and in the Silver Reef district (fig. 1). Significant deposits occur in most of these areas, but the boundaries of favorable ground have not been defined.

In the Circle Cliffs and Capitol Reef areas, uranium deposits occur mainly in the Shinarump member of the Chinle; and, because the Shinarump there is homogeneous, consisting mainly of a clean massive sandstone, these areas appear less favorable than the three main belts described above (fig. 5). The area near the Circle Cliffs pinchout, on the other hand, may be considered favorable, though no significant deposits have yet been found there (fig. 2).

In the Poison Spring Canyon area, small deposits of uranium and copper minerals occur in beds of siltstone and lenticular medium-grained sandstone in the mudstone unit below the Moss Back. The Moss Back member, in which no deposits are known to have been found here, is homogeneous; it consists of a clean massive sandstone. This area, therefore, seems unlikely to contain significant deposits in Triassic formations.

Many significant uranium deposits in the lower Chinle are being mined near Cameron and Holbrook, Ariz., in the vicinity of the Little Colorado River (fig. 1) (Finch, 1955). In the Defiance Uplift area (fig. 1) anomalous radioactivity has been detected in siltstone beds of the Chinle, but no ore deposits have been found. Weak showings of uranium minerals associated with carbonaceous material occur in the Shinarump member near Cameron and to the northwest near Fredonia, Ariz.

The deposits in the Chinle near Cameron and Holbrook are associated with charcoal-like material and bentonite in poorly consolidated sandstone lenses and channels. Chinle rocks that are normally red or gray have been altered to a peculiar yellow-brown near the deposits, but the altered rocks do not contain uranium. Most of the deposits contain copper and cobalt minerals.

The Cameron-Holbrook area, which is over 100 miles long, was examined only in a cursory manner, and the favorable parts of it were not defined. Some of the largest deposits in it lie just east of Cameron, and others east and southeast of Holbrook.

In House Rock Valley, Utah-Arizona, a little uranium is found in the Shinarump member of the Chinle and in the Wingate sandstone (fig. 1). Here the Shinarump pinches out and is affected by small collapse features accompanied by alteration, like those in the San Rafael Swell. The deposit in the Wingate appears to be a result of ground-water concentration along fractures like those in the Wingate at Temple Mountain. Because of these similarities to known favorable areas, the House Rock Valley area seems likely to contain significant deposits.

A few small deposits occur in the Chinle formation in the Silver Reef district, Washington County, Utah._/ The Chinle also

_/ Stugard, Frederick, Jr., 1954, Physical exploration for uranium during 1951 in the Silver Reef district, Washington County, Utah: U. S. Geol. Survey open-file report, 57 p., 13 figs.

contains deposits north of Meeker, Colo., and at other widely scattered localities on the Colorado Plateau.

Relation of deposits to structure and igneous rocks

Many of the structures on the Colorado Plateau have influenced the processes of sedimentation, particularly the deposition of the continental sediments of Triassic and Jurassic age. (See figure 2.) Most evident and significant is the influence of the salt anticlines on the deposition of the Moss Back member of the Chinle formation. Contrary to the prevailing opinion of R. G. Luedke and E. M. Shoemaker /,

/ See footnote p. 31.

I believe that other structures or more properly their antecedents such as monoclines and broad domes may have affected the deposition of the Shinarump and Moss Back members of the Chinle. These structures include the Monument upwarp, the Circle Cliffs uplift, the East Kaibab monocline, and Echo Cliffs monocline, and possibly others. The Monument upwarp, which affected a roughly circular area more than 25 miles across had no more than a hundred feet of maximum relief (fig. 2). This topographic high could have been due to differential erosion or to a slight doming. Evidence of regional doming is lacking; the Moenkopi beds in the high area are noticeably different from those in adjacent areas; there is no angular unconformity between the Moenkopi and the overlying beds; and the exposed formations do not thin over the dome. Finnell (1955), however, by detailed study of a single channel of Shinarump in White Canyon, has shown that before the deposition of the Shinarump the Moenkopi underwent slight monoclinal folding which affected the course of the stream that cut the channel. Stokes (1954) had previously concluded that the Monument upwarp exerted some influence on stream directions in the Salt Wash member of the Morrison formation. The area of nondeposition of the Shinarump is essentially within the south-central part of the Monument upwarp area. The trends of Shinarump channels in the southern part of the Monument upwarp area (fig. 5) tend to support the hypothesis of doming. The relation of the pinchouts of Shinarump to the Circle Cliffs uplift, the East Kaibab monocline, and the Echo Cliffs monocline is even less clear, but pinchouts can be observed along these structures. It therefore seems likely that pinchouts, channels, and mixed sediments that may have been controlled by structures produced physical and chemical traps for later deposition of the ore metals.

The spatial relation of the uranium deposits in the Triassic formations to regional structures is not easily determined because the outcrop pattern of the Triassic ore-bearing beds is controlled for the most part by structures (fig. 2). However, six of the seven largest deposits in Triassic rocks are on the flanks of major structures, and it seems that this relation is due, in part, to the effect of antecedent structures on the deposition of the ore-bearing beds. Structures in existence in Late Cretaceous or early Tertiary time, the more or less accepted time of mineralization, must have influenced the movement of ore-bearing solutions and the position of many deposits.

There is no field evidence for distinct joint or fault control of the majority of deposits in the Chinle. A few uranium deposits in the Wingate are controlled by fractures, but they contain only secondary minerals.

Whether the uranium deposits in the Triassic and Jurassic formations are distributed concentrically around major igneous centers such as the laccolithic mountains is uncertain. Reinhardt (1952), however, believes that there is a zoning of uranium deposits around the La Sal, Henry, and Abajo Mountains; and Shoemaker (oral communication) offers evidence for a zoning of copper deposits around the La Sal Mountains.

Uranium-bearing sedimentary rock occurs in association with some of the Tertiary plugs and diatremes in Monument Valley, and also near the Hopi Buttes and in some Tertiary igneous rocks at other scattered localities. A small amount of ore has been shipped from a diatreme among the Hopi Buttes, in Navajo County, Ariz. (Shoemaker, 1956).

COMPARISON OF URANIUM DEPOSITS IN THE TRIASSIC ROCKS AND IN THE MORRISON FORMATION

A question that often confronts a geologist who studies uranium deposits on the Colorado Plateau is this: Are the deposits in one formation, group, or area similar or dissimilar to those of another formation, group, or area? If a given small area contains uranium deposits near a single stratigraphic horizon, the geologist commonly assumes that there will be similar deposits near the same horizon in adjacent areas. Deposits in separate large areas, on the other hand, or in different formations, are not likely to be closely similar. Since most of the deposits on the Colorado Plateau are in either the Triassic Chinle formation or the Jurassic Morrison formation, a study was made of the similarities and dissimilarities between deposits in those formations.

The geology of the deposits in the Morrison has been described by Fischer (1942), Fischer and Hilpert (1952), and Weeks and Thompson (1954).

The uranium deposits of the Morrison formation occur mainly in the Salt Wash member which is mostly sandstone, although in northwestern New Mexico the overlying Brushy Basin member, which is mostly mudstone, contains important deposits in lenses of sandstone (Hilpert and Freeman, 1956). The deposits in the Salt Wash member, also, occur in lenticular sandstone layers rather than in the interbedded mudstone. In separate areas the deposits, although spotty, are largely confined to sandstone in a single stratigraphic zone and tend to be clustered in relatively small, poorly defined patches.

The chief minerals in the unoxidized portions of the deposits in the Morrison formation are uraninite, coffinite, and montroseite whereas those in the oxidized portions are carnotite and vanadium hydromica. Nearly all the deposits in the Morrison formation consist of vanadium-uranium ore with V_2O_5 5 to 20 times as abundant as U_3O_8; the average ore contains about 0.25 percent U_3O_8 and 2 percent V_2O_5. The ore minerals most commonly impregnate the sandstone, but high-grade replacements of fossil logs and branches by uranium and vanadium minerals are common. Some of the ore is in "rolls," which are peculiar elongate concretionary structures. In most places the long axes of the rolls tend to lie parallel to the fossil logs and the longest dimensions of the ore bodies. Most of the ore is in irregular tabular bodies generally parallel to the bedding of the sandstone. These bodies have an average thickness of 2 to 4 feet. The smallest are only a few feet across and contain only a few tons of ore; the largest are several hundred feet across and contain many thousands of tons of ore.

Uranium deposits occur in the Morrison formation over a wide area in western Colorado, eastern Utah, northeastern Arizona, and northwestern New Mexico (Finch, 1955). In some places, however, the deposits are clustered in favorable areas which have rather definite boundaries. One such area is the Uravan mineral belt in western Colorado (fig. 7) (Fischer and Hilpert, 1952). The deposits in that belt are larger than those nearby, outside of it. They contain 5 to 10 times as much V_2O_5 as U_3O_8 and average about 0.25 percent U_3O_8 and 2.0 percent V_2O_5. Both the ore rolls and the fossil logs tend to lie about at right angles to the local trend of the mineral belt.

Uranium deposits in the Chinle and Morrison formations appear to be more similar than dissimilar. Also, the uranium and vanadium deposits in other formations on the Colorado Plateau are similar to those in the Chinle or Morrison. Some observed similarities together with factors of localization and guides to ore, are summarized below.

Deposits in the Chinle and Morrison formations, have the following similarities:

(1) Unoxidized ores contain abundant pyrite and other sulfide minerals; oxidized ores are stained with limonite, which coats individual sand grains.

(2) The host rocks contain abundant interstitial white clay, derived from volcanic material.

(3) The uranium minerals are generally associated with abundant carbonaceous material.

(4) The deposits are in fluviatile sediments and appear to be controlled by permeability and porosity.

(5) The deposits are commonly found in light-colored gray, green, or light-brown rock rather than in dark reddish rock, and mudstone contained in an ore-bearing layer or underlying it is also commonly light-colored. The light colors are evidently due to alteration. Alteration of mudstones is less important as a guide to ore in the Triassic formations than in the Morrison formation (Weir, 1952), because in the Triassic rocks alteration is more widespread and there is rarely any marked local thickening of the altered zones beneath the uranium deposits.

(6) Most of the deposits are in either channels or lenses. The amount of thickness is not as important as the change in thickness; thick lenses and channels have more room for large deposits; but a few thin ones, also, contain large deposits.

(7) Most of the significant deposits lie in clusters that in some places form mineral belts with rather well-defined boundaries.

(8) The deposits occur in certain clastic rocks in restricted stratigraphic zones; each zone is overlain by a thick mudstone sequence of rocks.

Deposits in the Chinle formation differ in the following respects from those in the Morrison:

(1) Uranium deposits in the Chinle are found in all kinds of sedimentary rocks, including sandstone, conglomerate, siltstone, limestone, shale, and mudstone, whereas deposits in the Morrison are confined to sandstone and mudstone of rather uniform characteristics.

(2) In the Chinle, vanadium-uranium, copper-uranium, and uranium (vanadium and copper minor) deposits are all well represented, whereas most of the deposits in the Morrison are of the vanadium-uranium type.

(3) In the Chinle, it is often hard to distinguish uranium-bearing rock from barren rock; in the Morrison, uranium-bearing sandstone can readily be distinguished by its color.

ORIGIN

To understand fully how the uranium deposits in the Colorado Plateau were formed, we would have to know: 1) the source of the metals, 2) the source and nature of the mineralizing solutions,

3) the time of mineralization, and 4) the factors that determined localization of the deposits.

The first two of these are a matter of conjecture, but it seems likely that the uranium and associated metals were derived from syngenetic concentrations in the mudstone beds that overlay the ore-bearing rocks, or in the ore-bearing beds themselves, and that the leaching-out and transportation of the metals were largely the work of ground water. The time of mineralization for both the Chinle and the Morrison has been placed, as a result of isotopic age determinations on uraninite samples from both formations in late Mesozoic or early Tertiary time (Stieff, Stern, and Milkey, 1953). This fact, as pointed out by Stieff and others, suggests a common origin for these deposits.

The causes of localization are better known than the source and time of mineralization, and they are of greater practical importance, because they have proved to be the best guides in the search for new ore deposits and districts. These causes must include pinchouts of the Triassic ore-bearing beds, continuous thick layers of mudstone overlying the thin Triassic ore-bearing beds, the channels and lenses associated with the mid-Triassic surface of unconformity, and the abundance of carbonaceous material and mudstone in the channels. The movement of the mineralizing solutions in the Triassic rocks appears to have been controlled regionally by the mid-Triassic unconformity, the impervious overlying mudstone cap, and the pinchouts of the ore-bearing beds. The solutions must have flowed along the channels on the old erosion surface. Localization of deposits within these channels may have been controlled by physical conditions, such as reduction of permeability due to interbedded mudstone or differences in cementing and sorting; or to chemical conditions, such as the reducing effect of carbonaceous material, the ability of clay minerals to absorb uranium and vanadium, and the susceptibility of such materials as carbon, calcium carbonate, and clay to replacement.

SUMMARY AND CONCLUSIONS

Most of the uranium ore in the Triassic rocks of the Colorado Plateau occurs in channels or lenses of the Shinarump and Moss Back members of the Chinle formation. In general the deposits are tabular and follow the bedding; they range in size from a few tons to hundreds of thousands of tons. Although some of the deposits are mined only for uranium, others contain important amounts of vanadium or copper. The larger vanadium-uranium deposits generally contain about three times as much vanadium as uranium. The ore minerals are disseminated in the rock and commonly replace carbonaceous material and interstitial cement. The deposits in the Morrison formation and the Triassic rocks have more points of similarity than of dissimilarity.

It seems most probable that ground water either leached the constituents of the ores from overlying mudstone beds and carried them downward, or leached the ore constituents from the ore-bearing beds themselves and carried them laterally, and redeposited them in favorable environments during early Tertiary time.

The results of this study indicate that three belts, comprising about 20 percent of the area underlain by potentially ore-bearing Triassic rocks, are especially likely to contain significant deposits.

Each belt of favorable ground was delineated on the basis of the distribution of channel systems along the pinchout of ore-bearing beds, geologic guides to ore, and rather widely scattered ore deposits of significant size. Although only three favorable belts have been outlined, it might be possible with further study to outline others, and there are known to be areas of favorable ground whose boundaries have not yet been traced.

Below is a list of guides to ore in the Triassic formations, in order of importance:

1. Pinchout of ore-bearing beds
2. Channels and lenses; channel systems
3. Abundant mudstone beds interbedded with sandstone, particularly near the bottoms of channels
4. Abundant carbonaceous material
5. Light-colored sediments
6. Sulfide minerals, especially copper sulfides.

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