Uranium Deposits of the Moab, Monticello, White Canyon, and Monument Valley Districts Utah and Arizona

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CONTRIBUTIONS TO ECONOMIC GEOLOGY

GEOLOGICAL SURVEY BULLETIN 1222-H

Prepared on behalf of the
U.S. Atomic Energy Commission

UNITED STATES GOVERNMENT PRINTING OFFICE WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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URANIUM DEPOSITS OF THE MOAB, MONTICELLO, WHITE CANYON, AND MONUMENT VALLEY DISTRICTS, UTAH AND ARIZONA

By H. S. Johnson, Jr., and William Thordarson

ABSTRACT

Uranium deposits in the Moab, Monticello, White Canyon, and Monument Valley districts are similar in habit, and probably in origin, to uranium deposits elsewhere on the Colorado Plateau. Most of these deposits are elongate tabular bodies in fluvial sandstone and are oriented roughly parallel to bedding and sedimentary trends. Although widely distributed geographically, most of the deposits occur in a few stratigraphic units. Primary sedimentary features, such as regional and local pinchouts and facies changes, individual channel scours, and thick sandstone lenses, seem to be the principal controls of ore deposits and of favorable ground. A few fault-controlled uranium and copper deposits occur in the four districts, but structural controls are not clearly defined for most of the uranium deposits. Some structural features, such as salt anticlines, seem to have controlled favorable ground in that they influenced sedimentation of the ore-bearing units. The common occurrence of copper deposits in faults and adjacent fractured ground and of uranium deposits in sandstone with no apparent relation to faults or fractures suggests formation of the two different types of deposits by different ore solutions but does not preclude formation as part of a continuous sequence of mineralization.

Uranium occurs in many formations in the Moab, Monticello, White Canyon, and Monument Valley districts, but significant ore deposits and appreciable potential reserves are apparently confined to the Chinle and Morrison Formations of Late Triassic and Late Jurassic age, respectively, and possibly to the Cutler Formation of Permian age. Combined indicated and inferred reserves for the four districts are a little less than 25 percent of the total production through 1963, and potential reserves are about one to two times production plus indicated and inferred reserves.

The Chinle Formation has been the source of about 93 percent of the total uranium ore produced from the Moab, Monticello, White Canyon, and Monument Valley districts through 1963 and contains about 99 percent of the indicated and inferred reserves. Potential reserves in the Chinle are virtually confined to large hidden ore deposits (10,000 to several hundred thousand tons in size) probably present in the lowermost part of the formation in inferred belts of favorable ground: (1) on the southwest flanks of the Lisbon Valley and Moab anticlines,

(2) within the reconstructed boundaries of the Elk Ridge-White Canyon channel system and its buried eastern extension, (3) east of the Monument 2 mine area in the Monument Valley district, and (4) in the area of relatively discontinuous Moss Back within a few miles of the Moss Back's northeastern regional pinch-out. Outside these favorable areas, ore deposits in the Chinle probably are so small and scattered as to contain no appreciable potential reserves.

The Morrison Formation, in particular the Salt Wash Member, of Late Jurassic age has been the source of about 7 percent of the total uranium ore produced from the Moab, Monticello, White Canyon, and Monument Valley districts through 1963 and contains about 1 percent of the indicated and inferred reserves. Potential reserves in the Morrison Formation are for the most part in the Salt Wash Member in ore deposits 1,000 to several tens of thousands of tons in size. These ore deposits are mostly confined to belts of favorable ground coextensive with the trace of ancient channels on the Salt Wash alluvial plain. Outside these favorable belts, deposits in the Salt Wash are expected to be so small and scattered as to contain no appreciable potential reserves.

The presence of uranium deposits 1,000–10,000 tons or more in size in the Brushy Basin Member of the Morrison Formation in the Monticello district indicates that the Brushy Basin may contain appreciable potential reserves of low-grade ore and subore-grade uranium-bearing rock.

INTRODUCTION

This report summarizes the geologic relations and appraises the potential of the uranium deposits of the Moab, Monticello, White Canyon, and Monument Valley districts in Grand and San Juan Counties, Utah, and Navajo and Apache Counties, Ariz. (fig. 1). This is the last of four reports by the authors concerning the uranium resources of southeastern Utah (Johnson, 1957; 1959a, b).

Fieldwork was done during the summer of 1956 by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

Moab, Monticello, and Blanding are the area's main population centers. The principal highways are U.S. Route 160 and Utah Routes 46, 47, 95, and 128, from which secondary roads and truck trails provide limited access to most of the uranium mines.

The districts described in this report are largely in the Canyon Lands section of the Colorado Plateaus physiographic province (Fenneman, 1931, p. 306–312). They are characterized by high plateaus, mesas, and benches and by deep canyons. The Colorado and San Juan Rivers are the major streams of the region and are the only through-flowing streams. Deep canyons have been cut by these streams, and the resultant lowering of local base level has caused intricate dissection of the uplands. The lowest point in the four districts is 3,286 feet above sea level in the canyon at the junction of the San Juan and Colorado Rivers. The highest altitudes are 11,445 feet in the Abajo Mountains and 13,089 feet in the La Sal Mountains.

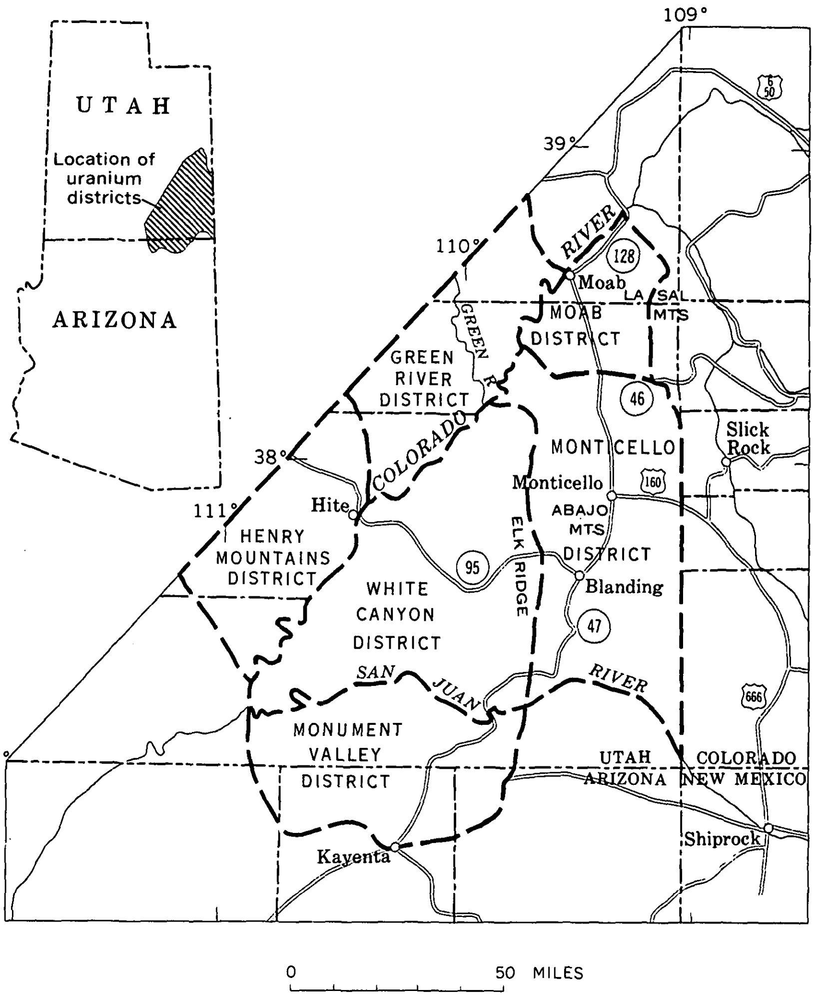

FIGURE 1.—Index map of parts of Utah, Arizona, Colorado, and New Mexico, showing location of Moab, Monticello, White Canyon, and Monument Valley districts.

Except for the deeper canyons and the isolated mountain areas, most of the country is 4,000–8,000 feet above sea level. The principal topographic features are the La Sal Mountains; the Abajo Mountains; Elk Ridge; the elongate troughs of Lisbon, Moab, and Castle Valleys; and the canyons of the Colorado and San Juan Rivers.

The climate of the region is semiarid. Precipitation varies from less than 10 inches a year in the lower altitudes to a little more than 15 inches a year at altitudes above 8,000 feet. Most of the rainfall occurs as brief local thundershowers. During these rains the surface runoff commonly reaches flood proportions in washes and along stream courses that are dry most of the time. Temperatures range from lows of −10° to −25°F in winter to highs of 100° to 120°F in summer. Daily temperatures often vary as much as 40°.

Much of the area of the four districts is within the province of northern desert-shrub vegetation and is characterized by sagebrush, rabbitbrush, shadscale, greasewood, yucca, and salt sage. Piñon and juniper are common at slightly higher altitudes; and above about 8,000 feet, yellow pine, aspen, spruce, balsam, and Douglas-fir occur.

Uranium-production and ore-reserve records compiled by the Grand Junction Operations Office of the U.S. Atomic Energy Commission, ore-reserve estimates and geologic observations made by the authors, data contained in numerous reports of the U.S. Atomic Energy Commission and the U.S. Geological Survey, as well as unpublished data in the files of these two organizations, were all used in this study.

Fieldwork consisted of reconnaissance visits to most of the known uranium deposits of the Moab, Monticello, White Canyon, and Monument Valley districts. At each deposit an attempt was made to determine the stratigraphic position of the ore-bearing unit; lithologic, stratigraphic, and structural controls affecting the deposit; indicated and inferred reserves; ore trends or the trend of controlling structural features such as ancient stream channels; and ore potential in the immediate area. These data were compiled and synthesized in an attempt to recognize controls of ground favorable for uranium deposits, to delineate these areas of favorable ground, and to appraise the uranium ore potential of the four districts.

The authors are indebted to many colleagues for information and discussions of geologic problems of the region, and particularly to R. P. Fischer for his aid in the preparation of the report. I. J. Witkind provided recent information concerning the igneous rocks.

HISTORY OF THE DISTRICTS

Deposits of uranium and vanadium ores were reported from southwest Colorado and southeast Utah as early as 1898. In 1905, Boutwell (1905, p. 203–207) described vanadium-uranium-copper ores in faulted and fractured zones in sandstone in the Richardson Basin area of what is now called the Moab district. In that same year, Ransome (Hillebrand and Ransome, 1905, p. 14–16) described carnotite deposits in the McElmo Formation—now called Morrison Formation—on La Sal Creek, just east of the Moab and Monticello districts.

During 1909–29, Gregory (1917; 1938) investigated the area now largely included in the White Canyon and Monument Valley districts. In 1920, Butler (1920, p. 616–617, 621–622) described uranium, vanadium, and copper deposits in sandstone in southeastern Utah and noted the presence of uranium in the White Canyon district at the Blue Dike copper prospect, now known as the Happy Jack uranium mine. In 1926–28 Baker (1933; 1936) studied the geology of the Moab and Monument Valley districts.

During World War II, the Union Mines Development Corp., on behalf of the Manhattan Engineer District, thoroughly investigated the vanadium-uranium deposits in the Morrison Formation in the Moab and Monticello districts as part of a general appraisal of Colorado Plateau uranium resources. This study showed that small to fairly large amounts of vanadium-uranium ore were present in many small scattered ore deposits in the Morrison Formation in southeast Utah.

Since 1948, the U.S. Atomic Energy Commission and the U.S. Geological Survey have carried on extensive geological investigations and exploration of the uranium-bearing formations in the Moab, Monticello, White Canyon, and Monument Valley districts as part of a general study of the uranium resources of the Colorado Plateau.

Prior to 1948 there was only intermittent mining on a moderate scale for vanadium and uranium ores in the Moab, Monticello, and Monument Valley districts. According to Boutwell (1905, p. 207) several small shipments of uranium ore were made from the Richardson Basin area during 1902–4 in an effort to develop a source of radium. Small-scale production of uranium ore began in 1911 from several deposits in the Morrison Formation in the Moab and Monticello districts. During World War I the demand for vanadium for the steel industry stimulated increased prospecting and production which lasted into the 1920's. In the late 1930's vanadium mining was revived and lasted until early 1944; during this period, outcrops were thoroughly prospected for vanadium deposits, and mills for processing the vanadium ore were built at Monticello and on Cottonwood Creek about 7 miles southwest of Blanding. In 1948 the U.S. Atomic Energy Commission began to buy uranium ore, and prospecting, mining, and production of uranium ore increased steadily for the next several years.

GEOLOGIC SETTING

The sedimentary rocks exposed in the Moab, Monticello, White Canyon, and Monument Valley districts have an aggregate thickness of about 6,000–7,000 feet and range in age from Pennsylvanian to Late Cretaceous (table 1). Tertiary and Quaternary deposits of gravel, landslide debris, alluvium, and windblown material are also present. The oldest rocks crop out in the canyon of the San Juan River in the southern part of the region and in breached salt anticlines in the northern part. The youngest rocks crop out only in downfaulted blocks in breached salt anticlines and as erosional remnants of upturned beds on the flanks of igneous intrusives of the La Sal and Abajo Mountains.

Except for a thick sequence of evaporites, black shale, limestone, and marine sandstone of Pennsylvanian and Permian age, most of the exposed sedimentary rocks are of continental origin and consist of sandstone, siltstone, and mudstone. The dominant colors are red and brown, though gray and buff are not uncommon.

TABLE 1.—*Generalized section of sedimentary rocks exposed in the Moab, Monticello, White Canyon, and Monument Valley districts, southeast Utah and northeast Arizona*

[In part after Baker and Reeside (1929), Baker (1933; 1936; 1946), Dane (1935), Gregory (1938), McKnight (1940), S. K. Smith (written commun., 1946), Craig and others (1955), Stewart and others (1959), and Carter (1957)]

System	Series	Group and formation	Member	Thickness (feet)	Character of rocks
Cretaceous	Upper Cretaceous	Mancos Shale		800+	Dark-gray marine shale.
		Dakota Sandstone		0–200	Light-brown sandstone and conglomerate and gray carbonaceous shale and mudstone; locally contains thin coal seams.
		Unconformity			
	Lower Cretaceous	Burro Canyon Formation		60–260	Light-brown massive and cross-bedded conglomeratic sandstone and green and gray-green mudstone; locally contains thin discontinuous beds of limestone, cherty limestone, and calcareous sandstone.
Jurassic	Upper Jurassic	Morrison Formation	Brushy Basin Member	200–450	Variegated bentonitic mudstone and siltstone containing thin scattered sandstone and conglomerate lenses.
			Westwater Canyon Member	0–250	Interbedded yellowish-brown fine- to coarse-grained sandstone and minor amounts of greenish-gray to reddish-brown silty and sandy claystone. Present only in southern part of Monticello district.
			Recapture Member	0–200	Interbedded grayish-red silty and sandy claystone and thin lenses of light-brown fine- to medium-grained sandstone. Present only in southern part of Monticello district.
			Salt Wash Member	100–550	Yellowish-brown, gray-white, and light-red lenticular fine-grained to conglomeratic sandstone containing interbedded red and green mudstone.
		San Rafael Group: Bluff Sandstone		0–185	White to gray-brown thick-bedded to massive medium-grained sandstone. Present only in southern part of Monticello district.
		San Rafael Group: Summerville Formation		25–100+	Thin-bedded ripple-marked reddish-brown muddy sandstone and shale.
		San Rafael Group: Entrada Sandstone		300–400	Reddish-brown to white thick-bedded to massive sandstone.
	Upper and Middle Jurassic	San Rafael Group: Carmel Formation		20–100+	Red muddy sandstone and sandy mudstone.

TABLE 1.—*Generalized section of sedimentary rocks exposed in the Moab, Monticello, White Canyon, and Monument Valley districts, southeast Utah and northeast Arizona*—Continued

System	Series	Group and formation		Member	Thickness (feet)	Character of rocks
			Unconformity(?)			
Triassic(?) and Jurassic	Upper Triassic(?)	Glen Canyon Group	Navajo Sandstone		300–880	Buff to light-gray and white massive crossbedded friable sandstone.
Triassic(?)	Upper Triassic(?)	Glen Canyon Group	Kayenta Formation		100–300	Reddish-brown irregularly bedded sandstone and shaly sandstone containing thin beds of limestone and limestone-pebble conglomerate.
Triassic	Upper Triassic	Glen Canyon Group	Wingate Sandstone		200–350	Reddish-brown to buff massive crossbedded fine-grained well-sorted sandstone.
Triassic	Upper Triassic	Chinle Formation		Church Rock Member	50–350	Reddish- to light-brown thin-to thick-bedded sandy siltstone.
Triassic	Upper Triassic	Chinle Formation		Owl Rock Member	150–450	Pale-red to reddish-brown thin- to thick-bedded siltstone and thin local reddish to greenish-gray limestone beds.
Triassic	Upper Triassic	Chinle Formation		Petrified Forest Member	0–700	Variegated red, purple, green, and yellow bentonitic claystone and clayey sandstone; intertongues with Owl Rock Member to the north.
Triassic	Upper Triassic	Chinle Formation		Moss Back Member	0–150	Yellowish- to greenish-gray fine- to medium-grained sandstone, conglomeratic sandstone, and conglomerate.
Triassic	Upper Triassic	Chinle Formation		Monitor Butte Member	0–200	Greenish-gray and minor amounts of pale-reddish-brown bentonitic mudstone and clayey sandstone; contorted and slumped bedding common.
Triassic	Upper Triassic	Chinle Formation		Shinarump Member	0–200	Yellowish-gray fine- to coarse-grained sandstone, conglomeratic sandstone, and conglomerate; contains abundant green mudstone lenses, carbonaceous material, and silicified wood in places.
Triassic	Upper Triassic	Chinle Formation		Mottled unit	0–250	Purplish-red siltstone to coarse gray- to pinkish-white arkosic grit and conglomeratic sandstone; frequently characterized by mottled purple, red, white, yellow, and brown coloration.
		Unconformity				
Triassic	Middle(?) and Lower Triassic	Moenkopi Formation			0–940	Reddish-brown evenly bedded ripple-marked cross-laminated siltstone and fine-grained sandstone.
Triassic(?)		Moenkopi Formation		Hoskinnini Tongue	0–120	Pale-reddish-brown thin- to thick-bedded siltstone and fine-grained sandstone.
		Unconformity				

TABLE 1.—*Generalized section of sedimentary rocks exposed in the Moab, Monticello, White Canyon, and Monument Valley districts, southeast Utah and northeast Arizona*—Continued

System	Series	Group and formation	Member	Thickness (feet)	Character of rocks
Permian		Cutler Formation	White Rim Sandstone Member	0–60	Very light gray to yellowish-gray fine- to medium-grained crossbedded sandstone.
	Lower Permian		De Chelly Sandstone Member	0–370	Buff to light-reddish-orange massive crossbedded very fine- to medium-grained sandstone.
			Organ Rock Tongue	100–690	Reddish-brown siltstone and sandy shale; minor amounts of fine-grained crossbedded sandstone.
			Cedar Mesa Sandstone Member	400–700	White to pale-reddish-brown massive crossbedded fine- to medium-grained sandstone.
			Halgaito Tongue	0–470	Reddish-brown siltstone to very fine grained sandstone; contains thin beds of gray limestone.
Pennsylvanian and Permian		Rico Formation		0–575	Buff, red, and purple arkosic sandstone and conglomerate and thin marine limestone beds in north part of area; grades into fossiliferous gray limestone interbedded with red and gray sandstone and red mudstone and shale in southern part of area.
Pennsylvanian	Upper Pennsylvanian	Hermosa Formation	Upper member	430–1,800	Fossiliferous bluish-gray limestone interbedded with gray cherty limestone; gray, black, blue, and red shale; and gray sandstone.
	Middle Pennsylvanian		Paradox Member		Salt, anhydrite, and gypsum with interbedded black and brown shale; crops out only in intrusive masses in breached salt anticlines.

Over most of the area of the Moab, Monticello, White Canyon, and Monument Valley districts the sedimentary rocks are flat to gently dipping. In a few places, dips as steep as 90° are associated with broad anticlinal folds, sharp monoclines, and domes due to flowage of salt or the intrusion of igneous rocks. Virtually all faults in the area are normal. The Lisbon Valley fault is associated with a salt anticline, and it has a maximum displacement of 5,000 feet; most faults in the region, however, have displacements of 300 feet or less.

Intrusive bodies of igneous rock consist of dikes, sills, stocks, and laccoliths in the La Sal and Abajo Mountains and dikes and volcanic necks in the Monument Valley district.

SEDIMENTARY ROCKS

The characteristics of the sedimentary rocks exposed in the Moab, Monticello, White Canyon, and Monument Valley districts are summarized below. Units containing significant uranium deposits are discussed in more detail than those that do not contain known ore. Detailed descriptions and correlations of these rocks have previously been given by Baker and Reeside (1929); Baker (1933, 1936, 1946); Dane (1935); Gregory (1938); McKnight (1940); Hunt and others (1953); Craig and others (1955); Robeck (1956); Stewart, Williams, Albee, and Raup (1959); Finnell, Franks, and Hubbard (1963); Witkind and Thaden (1963); Thaden, Trites, and Finnell (1964); and Lewis and Campbell (1965).

HERMOSA FORMATION

The Hermosa Formation of Middle and Late Pennsylvanian age is the oldest outcropping stratigraphic unit in the region. It is exposed only in narrow strips in the canyons of the San Juan and Colorado Rivers, in some of the deeper tributary canyons, and in the breached centers of the Lisbon Valley, Moab, and Castle Valley anticlines. The Paradox Member is composed mostly of interbedded salt, anhydrite, gypsum, and black shale. It crops out only in intrusive masses associated with the Moab and Castle Valley anticlines and locally in the bottom of the Colorado River canyon a few miles below the junction of the Green and Colorado Rivers. To the southwest of these exposures the Paradox grades into and interfingers with the fossiliferous limestone characteristic of the upper member of the Hermosa.

RICO FORMATION

The Rico Formation of Pennsylvanian and Permian age conformably overlies the Hermosa Formation. It crops out in the canyons of the San Juan and Colorado Rivers, in some of the deeper tributary canyons, and in the breached centers of the Lisbon Valley and Cane Creek anticlines. The Rico is composed of interbedded reddish-brown arkosic sandstone and gray marine limestone; it represents a transition zone between the predominantly marine Hermosa Formation and the continental Cutler Formation. According to Baker (1933, p. 29), the Rico changes from arkosic conglomerate in western Colorado and eastern Utah to predominantly fine-grained sandstone in the southwestern part of the Moab and Monticello districts; the source area was east of the Moab district, probably in the Precambrian rocks of the ancestral Uncompahgre Highland of western Colorado.

CUTLER FORMATION

The Cutler Formation of Permian age conformably overlies the Rico Formation and has large outcrop areas in parts of the Moab, Monticello, White Canyon, and Monument Valley districts. The Cutler is divided in ascending order into the Halgaito Tongue, Cedar Mesa Sandstone Member, Organ Rock Tongue, De Chelly Sandstone

Member, and White Rim Sandstone Member, but in no one area are all these units found together. In the northeastern part of the region the Cutler is undifferentiated and is composed of reddish-brown to purplish-red arkosic sandstone and conglomeratic sandstone. The Organ Rock and Halgaito Tongues are reddish-brown siltstone thought to represent westward extensions of the undifferentiated Cutler. The Cedar Mesa, De Chelly, and White Rim are massive, crossbedded eolian sandstones.

According to Stewart, Williams, Albee, and Raup (1959, p. 26), the rocks of the conglomeratic facies of the Cutler were deposited by westward-flowing streams which derived their sediment load from the rising granitic area of the ancestral Uncompahgre Highland in southwestern Colorado; the reddish-brown siltstone was probably deposited in quiet water in slowly sinking marginal continental basins; and the thick eolian sandstone was deposited in subaerial basins by winds which blew dominantly from the northwest. Uranium-copper and vanadium-uranium deposits occur in the Cutler in the zone of transition from white eolian sandstone to reddish-brown arkosic sandstone in the Moab and Monticello districts.

MOENKOPI FORMATION

The Moenkopi Formation of Early and Middle(?) Triassic and Triassic(?) age (including the Hoskinnini Tongue of Triassic(?) age) crops out in steep slopes over much of the northern, western, and southwestern parts of the region. In most places the Moenkopi appears to be in conformable contact with the underlying Cutler Formation, but over the Castle Valley and Moab anticlines the Cutler was folded and eroded before Moenkopi deposition (Baker, 1933, p. 33–34). Baker (1933, p. 35) also attributed the thinning of the Moenkopi over the Cane Creek anticline to uplift and erosion before deposition of the overlying beds. Absence of the Moenkopi over the crest of the Lisbon Valley anticline may be due to the regional pinchout of the formation (Stewart and others, 1959, p. 28), to local pinchout related to movement of salt in the anticline, or to uplift and erosion prior to deposition of the overlying beds.

The Moenkopi Formation is composed of reddish-brown evenly bedded ripple-marked siltstone and fine sandstone. It apparently is largely a tidal-flat deposit with fluvial deposits in some areas. The westerly dip of crossbeds in sandstone and the presence of coarse-grained arkosic sandstone and conglomeratic sandstone in the Moenkopi in western Colorado suggest derivation from the granitic ancestral Uncompahgre Highland of southwestern Colorado (Stewart and others, 1959, p. 31).

CHINLE FORMATION

The Chinle Formation of Late Triassic age crops out in steep slopes, ledges, benches, and mesa tops over large areas of the four districts. The Chinle unconformably overlies the Moenkopi Formation, and basal beds of the Chinle commonly fill ancient stream channels cut in the Moenkopi. Over the Moab and Cane Creek anticlines the Moenkopi was eroded prior to Chinle deposition (Baker, 1933, p. 36–37).

In this region the Chinle Formation is divided in ascending order into a mottled unit and the Shinarump, Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock Members; not all are present at any one place. Locally in the Moab and Monticello districts the basal beds of the Chinle are similar in lithology, stratigraphic position, and probable origin to the Temple Mountain Member of the Chinle (Robeck, 1956) in the San Rafael Swell, Utah. In this report these basal beds are referred to informally as the mottled unit. The mottled unit and the Shinarump, Monitor Butte, and Moss Back Members were included in the Shinarump Conglomerate of most earlier reports (Baker, 1933, 1946; McKnight, 1940; Hunt and others, 1933).

The Chinle Formation is discussed in some detail because it is one of the two principal uranium-bearing formations in the Moab, Monticello, White Canyon, and Monument Valley districts.

MOTTLED UNIT

Beds assigned in this report to the mottled unit are present locally in the northern parts of the region. The thickness varies greatly, ranging from 0 to more than 200 feet within a few thousand feet along the outcrop. The unit is generally characterized by purple, red, white, yellow, and brown mottling. It includes a grit and conglomerate deposit noted and described by Baker (1933, p. 37–38) and Dane (1935, p. 55–56) in the canyon of the Colorado River about 6 miles north-northeast of Moab. The deposit contains a high percentage of rounded quartz pebbles, some as much as 3 inches in diameter, and a few pebbles of metamorphic and igneous rock (Dane, 1935, p. 56). Deltaic crossbedding—having foreset beds dipping as much as 12° from the horizontal and truncated by flat-lying topset beds—in this deposit indicates a northwesterly direction of sediment transport (Baker, 1933, p. 38). A simlar deposit 100–200 feet thick makes up most of the basal part of the Chinle exposed at Lackey Basin (fig. 4) on the south side of the La Sal Mountains. The authors believe that it correlates with the mottled unit—exposed along the Colorado River and in the Green River and Henry Mountains districts (Johnson, 1959b)—and with the Temple Mountain Member

(Robeck, 1956) in the San Rafael Swell. See also Abdel-Gawad and Kerr (1963); Johnson (1964); Kerr and Abdel-Gawad (1964).

Coarse sediments in the mottled unit were undoubtedly derived from granitic terrane of the ancestral Uncompahgre Highland and were deposited by west- to northwest-flowing streams. Reworked Moenkopi silt and clay apparently make up a large part of the mottled unit at many places.

SHINARUMP MEMBER

The Shinarump Member is the basal unit of the Chinle Formation in part of the White Canyon and Monument Valley districts. Rocks in the northwestern part of the Moab and Monticello districts that were previously correlated with the Shinarump are now correlated with the Moss Back Member of the Chinle Formation (Stewart and others, 1959, p. 40). The Shinarump is composed dominantly of yellowish-gray fine- to coarse-grained sandstone, conglomeratic sandstone, and conglomerate, and it characteristically fills ancient channel scours cut into the underlying Moenkopi Formation. In places the Shinarump contains abundant green mudstone lenses, carbonaceous material, and silicified wood.

In the White Canyon and Monument Valley districts the Shinarump ranges in thickness from 0 to about 200 feet. Where present in the White Canyon district, the Shinarump is commonly less than 20 feet thick except where it fills channels scoured as deep as 50 feet into the underlying Moenkopi. Where present in the Monument Valley district, the Shinarump commonly averages 50–100 feet thick; in places it fills ancient scours as much as 2,000 feet wide and 150 feet deep (Witkind, 1956b, p. 235).

Study of the Shinarump in the White Canyon district has indicated that it was deposited in two ancient channel systems, one having a source area to the south in Arizona and the other having a source area to the east, perhaps in the granitic terrane of the ancestral Uncompahgre Highland in southwestern Colorado. The channel system from the east was described and named the Elk Ridge-White Canyon channel system by Johnson and Thordarson (1959).

Many important uranium deposits are known in the Shinarump Member in the report area.

MONITOR BUTTE MEMBER

The Monitor Butte Member (Witkind and Thaden, 1963) of the Chinle is present in the Monument Valley district and in the southern and central parts of the White Canyon district. It lies conformably on the Shinarump and overlaps that member to the northeast in the north-central part of the White Canyon district. The Monitor Butte is composed of greenish-gray and pale-reddish-brown bentonitic mudstone and clayey sandstone, and it ranges in thickness from about 200 feet in White Canyon to a featheredge about 15–20 miles north of White Canyon. Locally the member contains lenses of grayish-white fine- to coarse-grained sandstone lithologically similar to sandstone of the Shinarump Member.

MOSS BACK MEMBER

The Moss Back Member of the Chinle Formation overlies the Monitor Butte Member in the central part of the White Canyon district and overlaps the Monitor Butte to the northeast. In parts of the Moab and Monticello districts the Moss Back is the basal unit of the Chinle. The Moss Back is typically composed of yellowish-gray to greenish-gray fine- to medium-grained sandstone, conglomeratic sandstone, and conglomerate, and ranges in thickness from 0 to about 150 feet. In places it fills ancient stream channels scoured a few feet to a few tens of feet into the underlying unit.

Along a northwest-trending line passing about 2 miles south of the Dugout Ranch, the Moss Back changes abruptly from a continuous blanketlike deposit averaging about 50 feet in thickness southwest of the line to a thin lenticular unit seldom more than 25 feet thick northeast of the line (pl. 1).

Along a northwest-trending line crossing the Colorado River at the mouth of Indian Creek (pl. 1) the Moss Back appears to merge with and become indistinguishable from overlying Chinle rocks. The Chinle thins over the crest of the Cane Creek anticline (pl. 2), and recognizable Moss Back presumably was not deposited over the crest or northeast of the structure.

Greenish-gray sandstone, siltstone, and calcareous siltstone pebble conglomerate typical of the Moss Back are exposed in the basal part of the Chinle on the southwest flank of the Lisbon Valley anticline and contain important uranium deposits there. These rocks probably correlate with the Moss Back Member and were included in the Moss Back by Stewart, Williams, Albee, and Raup (1959, fig. 77).

Small to moderately large uranium deposits also are present in the Moab district where the Moss Back is the basal unit of the Chinle and is relatively thin and discontinuous.

PETRIFIED FOREST MEMBER

The Petrified Forest Member of the Chinle Formation overlies the Monitor Butte Member where the Moss Back is absent in Arizona and overlies the Moss Back where it is present in Utah. From a maximum thickness of about 700 feet in the Monument Valley district the Petrified Forest Member thins northward to a thickness of about 100 feet in the central part of the White Canyon district, where it loses identity by intertonguing with the overlying Owl Rock Member. The Petrified Forest is typically composed of variegated bentonitic claystone and clayey sandstone.

OWL ROCK MEMBER

The Owl Rock Member (Witkind and Thaden, 1963) of the Chinle overlies the Petrified Forest Member in the Monument Valley and White Canyon districts and grades laterally into the overlying Church Rock Member in the area near the junction of the Green and Colorado Rivers (Stewart and others, 1959, fig. 5).

The Owl Rock Member is typically composed of pale-red to reddish-brown thin- to thick-bedded siltstone and thin, local reddish- to to greenish-gray limestone beds. According to Stewart, Williams, Albee, and Raup (1959, p. 59), the Owl Rock is generally 150–250 feet thick in southeastern Utah but has an abnormal thickness of 350–450 feet in the White Canyon and Elk Ridge areas.

CHURCH ROCK MEMBER

The Church Rock Member (Witkind and Thaden, 1963) of the Chinle Formation overlies the Owl Rock Member and is present in Chinle outcrops throughout the Moab, Monticello, White Canyon, and Monument Valley districts (Stewart and others, 1959, fig. 5). The Church Rock is typically composed of reddish-brown to light-brown thin- to thick-bedded sandy siltstone and is about 50–350 feet thick. In the northern part of the Monticello district and in the northwestern part of the Moab district the Church Rock Member locally contains lenses of pale-red to light-brown fine-grained sandstone and minor amounts of red and green mudstone and carbonaceous material.

WINGATE SANDSTONE

The Wingate Sandstone of Late Triassic age overlies the Chinle Formation in the Moab, Monticello, White Canyon, and Monument Valley districts and commonly crops out as sheer cliffs. The Wingate is typically composed of reddish-brown to buff massive crossbedded fine-grained well-sorted sandstone and is predominantly eolian in origin. Its thickness ranges from about 200 to 350 feet (Stewart and others, 1959) and averages about 300 feet.

KAYENTA FORMATION

The Kayenta Formation of Late Triassic(?) age overlies the Wingate Sandstone in southeastern Utah and northern Arizona and commonly crops out in a narrow ledgy bench at the top of a Wingate cliff. The Kayenta is 100–300 feet thick and is typically composed of reddish-brown irregularly bedded sandstone and shaly sandstone and thin local beds of limestone and limestone pebble conglomerate.

NAVAJO SANDSTONE

The Navajo Sandstone of Jurassic and Triassic(?) age overlies the Kayenta Formation and crops out in a scarp with the Wingate and Kayenta Formations or in a hummocky surface rising above a base formed by the Kayenta Formation (Baker, 1933, p. 46). The Navajo, 300–880 feet thick, is predominantly eolian in origin and is typically composed of buff to light-gray and white massive cross-bedded friable sandstone.

CARMEL FORMATION

The Carmel Formation of Early and Middle Jurassic age overlies the Navajo Sandstone in the Moab, Monticello, White Canyon, and Monument Valley districts and commonly crops out as a bench between the Navajo and Entrada Sandstones. The Carmel is 20 to about 100 feet thick in southeast Utah and is typically composed of red muddy sandstone and sandy mudstone. According to Baker (1933, p. 49) part of it is marine in origin.

ENTRADA SANDSTONE

The Entrada Sandstone of Late Jurassic age overlies the Carmel Formation and crops out in cliffs or hummocky surfaces. The Entrada is predominantly eolian in origin and is typically composed of reddish-brown to white thick-bedded to massive well-sorted sandstone that is 300–400 feet thick in southeast Utah.

SUMMERVILLE FORMATION

The Summerville Formation of Late Jurassic age crops out in gentle to steep slopes above the Entrada Sandstone. The Summerville is typically composed of thin-bedded ripple-marked reddish-brown muddy sandstone and shale and is 25–100 feet or more thick in southeast Utah.

BLUFF SANDSTONE

The Bluff Sandstone of Late Jurassic age is present only in the southern part of the Monticello district, where it overlies the Summerville Formation and underlies the Morrison Formation. The Bluff thins northward from a maximum thickness of about 185 feet near the southern boundary of the Monticello district to a pinchout along an east-west line just south of Blanding, Utah. The Bluff is white to gray-brown thick-bedded to massive medium-grained cliff-forming sandstone.

MORRISON FORMATION

The Morrison Formation of Late Jurassic age has been divided in ascending order into the Salt Wash, Recapture, Westwater Canyon, and Brushy Basin Members. The Recapture and Westwater Canyon Members are present only in the southern part of the Monticello district and pinch out or become unrecognizable to the north near Blanding, Utah. The Salt Wash and Brushy Basin Members were originally deposited over the entire report area but have been removed by erosion from all of the Monument Valley district and parts of the other three districts. As one of the two principal uranium-bearing formations in southeast Utah, the Morrison Formation is discussed in some detail in this report.

SALT WASH MEMBER

The Salt Wash Member of the Morrison Formation averages about 300 feet in thickness in southeastern Utah and is composed principally of yellowish-brown, gray-white, and light-red lenticular fine-grained to conglomeratic sandstone interbedded with red and green mudstone. Carbonaceous material is sparse to abundant. According to Craig and others (1955, p. 125), the Salt Wash was formed as a fan on a large alluvial plain by a system of aggrading braided streams that diverged to the north and east from an apex in south-central Utah (pl. 3). Near the apex of the fan the Salt Wash is composed principally of thick blanketlike layers of coarse sandstone and conglomerate interbedded with a minimum of mudstone. Near the outer edges of the fan, in north-central Utah and west-central Colorado, the Salt Wash is dominantly mudstone containing minor amounts of sandstone in relatively discontinuous lenses. Between the inner coarse sandstone and conglomerate facies and the outer mudstone facies is an intermediate facies in which the Salt Wash is composed of interbedded sandstone and mudstone, either of which may constitute as much as 75 percent of the unit. The approximate position and trend of ancient trunk channel systems on the Salt Wash fan may be inferred from the thicker lobes shown on an isopach map of the member (pl. 3). In the field the trace of these trunk channel systems is indicated in some places by a slightly greater total thickness of the member, a larger percentage of sandstone in the member, and a greater than normal thickness of the sandstone lenses present in the member. The term "channel system" is not meant to imply a well-defined river channel which maintained its position throughout Salt Wash time; rather it is intended to represent the trace of one or more large braided streams which meandered back and forth within certain poorly defined limits on the Salt Wash fan.

Important deposits of uranium and vanadium ore occur in the Salt Wash Member at many places in the Moab and Monticello districts.

RECAPTURE MEMBER

The Recapture Member of the Morrison Formation ranges in thickness from 0 to 200 feet in southeast Utah and is composed of interbedded grayish-red, silty and sandy claystone and thin lenses of light-brown fine- to medium-grained sandstone. Near its northern limit in the vicinity of Blanding, the Recapture intertongues with and grades into the Salt Wash (Craig and others, 1955, p. 137).

Craig and others (1955, p. 140) recognized a conglomeratic sandstone facies, an intermediate sandstone facies, and an outer claystone and sandstone facies in the Recapture Member. These facies are analogous to the several facies of the Salt Wash Member. In southeast Utah the Recapture is confined to the claystone and sandstone facies and is predominantly claystone containing a few isolated lenses of sandstone or conglomerate.

WESTWATER CANYON MEMBER

The Westwater Canyon Member of the Morrison is typically composed of interbedded yellowish-brown fine- to coarse-grained sandstone and minor amounts of greenish-gray to reddish-brown silty and sandy claystone. It is as much as 250 feet thick in southeastern Utah; but northward, in the area between Blanding and Monticello, it intertongues with and grades into the lower part of the Brushy Basin Member. Craig and others (1955, p. 154) separated the Westwater Canyon Member into a conglomeratic sandstone facies and a sandstone facies. In southeast Utah the Westwater Canyon Member consists of only the sandstone facies.

BRUSHY BASIN MEMBER

The Brushy Basin Member of the Morrison ranges in thickness from about 200 to 450 feet in southeastern Utah. It is composed predominantly of variegated bentonitic mudstone and siltstone with thin scattered sandstone and conglomerate lenses. Locally the Brushy Basin contains thin limestone beds and beds of grayish-red to greenish-black siltstone that was probably deposited in small fresh-water lakes.

BURRO CANYON FORMATION

The Burro Canyon Formation of Early Cretaceous age is as much as 260 feet thick in southeastern Utah. It is typically composed of light-brown massive and crossbedded conglomeratic sandstone and green and gray-green mudstone. Where sandstone beds are lacking at the base of the Burro Canyon, the formation is difficult to distinguish from the mudstone beds of the underlying Brushy Basin Member of the Morrison Formation.

DAKOTA SANDSTONE

The Dakota Sandstone of Late Cretaceous age ranges from 0 to about 200 feet in thickness in southeastern Utah and is composed predominantly of light-brown sandstone and conglomerate and gray carbonaceous shale and mudstone, locally containing thin coal seams. According to Craig and others (1955, p. 161), the Dakota overlies the Burro Canyon Formation with regional disconformity. Carter (1957) gave further evidence of this disconformity and showed that sandstone beds of the Burro Canyon Formation were silicified prior to deposition of the Dakota.

MANCOS SHALE

The Mancos Shale of Late Cretaceous age is present in southeastern Utah in downfaulted blocks associated with salt anticlines and in erosional remnants around the La Sal and Abajo Mountains. It is more than 800 feet thick and is predominantly composed of dark-gray marine shale.

IGNEOUS ROCKS

The stocks and laccoliths of the La Sal and Abajo Mountains are the dominant igneous rocks in the Moab, Monticello, and White Canyon districts. These intrusive masses are composed mainly of quartz diorite porphyry, diorite and monzonite porphyries, and syenite porphyry (Hunt, 1956, p. 42; Witkind, 1964, p. 32). Their age is uncertain; they may be as old as latest Cretaceous (Shoemaker, 1956, p. 162) or as young as mid-Tertiary (Hunt and others, 1953).

In the Monument Valley district, dikes, volcanic rocks, and diatremes are common, are characterized by alkaline basalts, and range from monchiquite to minette (Shoemaker, 1956, p. 161; Witkind and Thaden, 1963, p. 51–54; Malde and Thaden, in Witkind and Thaden, 1963, p. 54–61). These rocks may be of middle or late Pliocene age (Williams, 1936, p. 148).

Recent work (Condie, 1964, p. 359) has disclosed a small syenite porphyry intrusion on the southwest flank of Navajo Mountain, a sedimentary dome long thought to be underlain by igneous rocks similar to those of the La Sal and Abajo Mountains (Baker, 1936, p. 71–72; Hunt and others, 1953, p. 148).

The Castle Valley plug, a gray-white sodic trachyte, is a nearly circular intrusion about 1,500 feet in diameter just north of the La Sal Mountains (Baker, 1933, p. 59).

Minor amounts of copper and uranium minerals are associated with a discontinuous rubble dike of mica-serpentine tuff at Garnet Ridge in the eastern part of the Monument Valley district (Shoemaker, 1957, p. 183; Witkind and Thaden, 1963, p. 61), but no other uranium deposits are known to be directly associated with igneous rocks in the four districts.

STRUCTURE

The regional structure of the Moab, Monticello, White Canyon, and Monument Valley districts is characterized for the most part by gentle dips on the flanks of major upwarps and shallow basins (pl. 2). These dips steepen abruptly in a few places into sharp monoclinal folds or asymmetrical anticlines and into local anticlinal or domal structures related either to the flowage of salt (from the Paradox Member of the Hermosa Formation) or to igneous intrusions. Faulting produced high-angle normal faults and grabens. The large monoclinal folds of this part of the Colorado Plateau are probably related to stretching and bending of the sedimentary rocks over high-angle normal or reverse faults in the Precambrian basement rocks.

The structure of the region can be roughly divided into two provinces separated by a northwest-trending line passing approximately through Monticello, Utah. Southwest of this line the regional structure is dominated by the north-trending Monument uplift, and most of the lesser structural features also trend north. Northeast of the dividing line the regional structure is dominated by northwest-trending salt anticlines (for example, the Moab and Cane Creek anticlines) and related belts of normal faults.

The salt anticlines are characterized by thickening in the underlying salt, and some show piercement of overlying strata by pluglike intrusions of salt. The anticlines probably began to form during Late Permian time, as indicated by thinning of the Cutler Formation over the crest of the Cane Creek anticline (Baker, 1933, p. 34) and by a slight angular unconformity between the Cutler and Moenkopi Formations over the crests of parts of the Cane Creek and Moab anticlines (McKnight, 1940, p. 51). Thinning of the Moenkopi Formation on the crests of these structures and, in some places, a slight angular unconformity between the Moenkopi and Chinle Formations indicate that movement of salt continued intermittently during Triassic time. Meander anticline, a narrow northeast-trending arch virtually coextensive with the inner canyon of the Colorado River near its junction with the Green River, is probably related to salt flowage that occurred after canyon cutting caused release of load in geologically recent time (McKnight, 1940, p. 130).

Upheaval Dome, in the area between the Green and Colorado Rivers, just west of the Moab and Monticello districts, is a local feature of considerable interest but uncertain origin (pl. 2). This small circular dome has been attributed to a salt intrusion (McKnight, 1940, p. 128) and also to igneous forces (Bucher, 1936, p. 1066). Recent geophysical work indicates a strong magnetic anomaly and a small positive gravity anomaly under Upheaval Dome (Joesting and others, 1955, p. 95) and suggests that the structure is related to an igneous plug. Another magnetic anomaly of similar magnitude—the Grays Pasture anomaly—occurs about 8.5 miles southeast of Upheaval Dome (H. R. Joesting and D. F. Plouff, oral commun., 1956), and a line through Upheaval Dome and the Grays Pasture anomaly intersects Lockhart syncline, a circular collapse structure, about 8.5 miles southeast of the Grays Pasture anomaly. Although seemingly no magnetic anomaly is associated with the Lockhart syncline (James Aubrey and D. F. Plouff, oral commun., 1956), conceivably this syncline too is related to igneous activity. Baker, however, considered it more likely that Lockhart syncline is due to flowage of salt away from the area of collapse (Baker, 1933, p. 70–71, 76).

Puffett, Weir, and Dodson (1957) described a group of small collapse structures along the northeast side of Spanish Valley near Moab, Utah, as follows:

> These structures occur in a belt, about half a mile wide and at least 10 miles long, that parallels the major northwest-trending folds and faults. The collapse structures are nearly oval in plan. Diameters range from less than 100 feet to about 1,500 feet. Displacements downward within them are greater than the width of the structures and range from a few hundred feet to 1,500 feet or more. The displaced part is commonly brecciated, but slickensides are absent; in some structures the sandstones have been decemented and have flowed steeply inward as shown by foliation. The boundaries of the collapse structures are sharp. The rock outside them generally shows no alteration other than the intrusion of small sandstone dikes and veinlets. Spanish Valley marks the structurally complex central part of the Moab salt anticline, and the collapse structures are probably related to solution at depth of underlying salt and carbonate rocks. The collapse structures are of Tertiary age; they involve Upper Cretaceous rocks and are overlain by lower Pleistocene gravels. The structures seem to be favorable sites for mineralization, somewhat similar to the uraniferous collapse structure at Temple Mountain, San Rafael Swell, Utah. However, none of the collapse structures of Spanish Valley are known to be mineralized.

Nearly all faults in the Moab, Monticello, White Canyon, and Monument Valley districts are of the high-angle normal type. Most have less than 300 feet displacement. The Lisbon Valley fault has the maximum vertical displacement—about 5,000 feet—and is associated with the Lisbon Valley salt anticline. A similar fault associated with the southeast end of the Moab anticline has a maximum displacement of more than 2,000 feet at one place (G. W. Weir, oral commun., 1957). These large faults are probably related to breaks in the Precambrian basement rocks. According to Joesting, Byerly, and Plouff (1956, p. 231), gravity surveys indicate that the maximum vertical displacement on the Moab fault increases from about 2,500 feet at the surface to about 5,000 feet in the crystalline basement. Apparently the difference in displacement between the upper and lower parts of this fault is due mainly to a greater thickness of Pennsylvanian and Permian rocks on the downthrown side of the fault. Zones of weakness represented by faults of this type may well have been responsible for the start of salt flowage in the salt anticlines of the east-central part of the Colorado Plateau. Later, solution and removal of the salt by ground water caused collapse of the salt anticlines and resulted in the formation of grabens and local complex block faults.

Low-grade copper deposits are associated with the Lisbon Valley fault, and uranium deposits occur in minor faults associated with the Cane Creek anticline and in faults in the Richardson Basin area of the Moab district (pl. 2).

URANIUM DEPOSITS

Most of the productive uranium deposits in the Moab, Monticello, White Canyon, and Monument Valley districts are in the Cutler, Chinle, and Morrison Formations (pl. 1). A few uranium deposits that have yielded small amounts of ore occur in the Hermosa, Rico, Moenkopi, Wingate, and Kayenta Formations. Most deposits in the Morrison and some in the Chinle yield byproduct vanadium. Copper is conspicuous in some deposits, especially in the Cutler and Chinle Formations.

The uranium deposits in the region are of two rather distinct types: (1) tabular deposits nearly parallel to the bedding of the host sandstone and (2) fracture-controlled deposits. Most deposits in the region—and all that have yielded large production—are of the tabular type. In these the ore minerals chiefly impregnate the sandstone but partly replace some of the sand grains, clay particles, and especially fragments of fossil wood. The ore minerals in fracture-controlled deposits in part fill fractures and faults and in part impregnate the adjoining sandstone. The fracture-controlled deposits are described in this report but are not considered in the resource appraisal, for none have yielded large production and thus at the present stage of development their resource potential seems to be relatively small. The tabular deposits have been called "bedded" (Johnson, 1957; 1959 a, b) to contrast them with the fracture-controlled deposits. Finch (1959) suggested the term "peneconcordant" for the tabular deposit.

MINERALOGY

Below the oxidized zone the common uranium minerals are, for the tabular deposits, uraninite or pitchblende [UO_2+] and coffinite

[$U(SiO_4)_{1-x}(OH)_{4x}$], and for the fracture-controlled deposits, uraninite. The common vanadium minerals in unoxidized tabular deposits are the oxide montroseite [$VO(OH)$] and three micaceous silicates—roscoelite [$K(Al, V)_2(Al, Si_3)O_{10}(OH, F)_2$], a vanadium-bearing hydrous mica, and a vanadium-bearing chlorite. In unoxidized fracture-controlled deposits vanadium is sparse, and generally no recognizable vanadium minerals are present. Copper occurs as the common sulfides chalcopyrite, bornite, and chalcocite in unoxidized deposits of both types.

In the oxidized zone many secondary minerals of uranium, vanadium, and copper are present, the group of minerals in a specific deposit depending mainly on the metal assemblage. In the vanadium-bearing uranium deposits, carnotite [$K_2(UO)_2V_2O_8 \cdot 1\text{–}3\ H_2O$] and tyuyamunite [$Ca(UO_2)V_2O_8 \cdot 5\text{–}8\frac{1}{2}\ H_2O$] are the common ore minerals. Under oxidizing conditions these minerals are stable, and little or no migration of uranium or vanadium occurs. The stable vanadium silicates common in the unoxidized ore deposits are also present in the oxidized deposits. In deposits containing uranium alone or both uranium and copper, a large variety of secondary minerals may form, including oxides, carbonates, sulfates, phosphates, arsenates, and silicates of either or both metals. Although some of these minerals are moderately stable at the outcrop, others are easily soluble, so both uranium and copper tend to migrate from the outcrop of these deposits. This factor is important to consider in exploration and appraisal.

Ore minerals and their habits were described in detail in a paper by Weeks, Coleman, and Thompson (1959).

Accessory minerals below the zone of oxidation are mainly sulfides. Pyrite and marcasite are common and are probably present in all deposits, but generally they are not abundant. Small amounts of galena and sphalerite are locally present. Traces of molybdenum, cobalt, nickel, and silver occur in many deposits, but these metals rarely form recognizable minerals below the zone of oxidation. The stain of iron oxides is common in the oxidized parts of all deposits, and in a few places cobalt bloom is recognized.

Introduced gangue minerals other than those that commonly cement sandstone are, for the tabular deposits, inconspicuous or absent. Calcite is a gangue mineral in a few fracture-controlled deposits.

FRACTURE-CONTROLLED DEPOSITS

In Richardson Basin at the north end of the Moab district, uranium, vanadium, and copper minerals occur in minor fractures in the Wingate and Kayenta Formations in a large downwarped or downfaulted block in a complex grabenlike structure (pl. 1, loc. 1). These fractures, which have yielded only a moderate amount of ore, had been tested to a depth of 65 feet in 1956. The recognized ore minerals are all secondary—carnotite, tyuyamunite, calciovolborthite, malachite, and azurite—and they are associated with calcite.

In Cane Springs Canyon, on the northeast flank of the Cane Creek anticline, uranium minerals occur along faults of small displacement in the Cutler Formation (pl. 1, loc. 2–5). Secondary uranium minerals and uranium-bearing petroliferous material (asphaltite?) form the ore at the surface, whereas at a depth of 200 feet the ore consists of uraninite in thin veinlets. No gangue minerals are recognized, but the wallrock shows some change in color due to alteration.

In a prospect in the southeast part of Lisbon Valley, copper and uranium and perhaps vanadium minerals are exposed along a fault that dropped the Burro Canyon Formation against the Salt Wash Member of the Morrison Formation. According to G. W. Weir (written commun., 1954), copper carbonates and oxides impregnate sandstone along the fault, along minor fractures in a zone parallel to the fault, and along bedding planes. Radioactive material is concentrated in limonite-stained silicified sandstone along a fracture close to the main fault.

Copper ore has been mined from sandstone of the Dakota and Burro Canyon Formations at the Big Indian and Pioneer mines in Lisbon Valley (pl. 1). Both deposits consist mainly of secondary copper minerals that impregnate sandstone and form narrow veinlets along fractures; remnants of the common copper sulfides are found in places (Butler and others, 1920). Both deposits are adjacent to the Lisbon Valley fault and associated fractures. Showings of copper minerals have been prospected in these formations and also in the Cutler and Hermosa Formations at other places along the Lisbon Valley fault and associated fractures (pl. 1). Anomalous radioactivity and even uranium-bearing samples have been reported by prospectors from these copper deposits, but no uranium ore has been mined.

Copper-silver ore has been mined from the Cashin mine on La Sal Creek in Colorado about 15 miles northeast of Lisbon Valley (Emmons, 1906). The deposit is virtually a fissure vein along a fault of small displacement where it cuts the Wingate and Chinle Formations. Copper sulfides and native copper are the principal ore minerals (Fischer, 1936). Theodore Botinelly (oral commun., 1958) found a small amount of uranium-bearing carbonaceous material coating ore minerals at one place in the mine. Uranium and radioactivity have not been found at any other place in the deposit, according to Botinelly.

TABULAR DEPOSITS

The tabular or "bedded" deposits in the Moab, Monticello, White Canyon, and Monument Valley districts are similar to those elsewhere in the Colorado Plateau region (Fischer, 1942, 1956; Finch, 1955). Though the tabular deposits are in general nearly parallel to the bedding of the sandstone, they are in detail somewhat irregular and crosscutting. The layers range in thickness from a few inches to 20 feet or more and in width from a few feet to more than a thousand feet. Although many deposits are small, most of the production in these districts has come from deposits containing at least 10,000 tons of ore; some deposits contain more than 100,000 tons of ore. Some deposits are irregular in plan but many tend to be elongate parallel to the sedimentary structures of the host sandstone. The thicker sandstone lenses and ancient stream channels are preferred loci for many deposits. The ore deposits tend to occur in clusters and belts having similar size and grade of ore body.

GRADE AND DISTRIBUTION OF METALS

In general the uranium deposits have rather well-defined limits, and ore-grade material commonly extends to or nearly to the edge of mineralized ground. In some mines or parts of mines the limit of mining is controlled by an assay wall, and in other places mining limits are controlled by a thinning of the ore layer, but generally the ore bodies are not surrounded by large masses of low-grade mineralized rocks. Some deposits of marginal or submarginal grade are known, however, and a few of these may be moderately large, but inasmuch as they have not been developed or thoroughly tested they cannot be accurately appraised at present.

Most ore mined in the region ranges from about 0.2 to 0.5 percent U_3O_8. Much of the ore that contains appreciable vanadium is treated at mills equipped to recover vanadium as a byproduct; these ores average 1–2 percent V_2O_5. Some copper-bearing uranium ore mined in the White Canyon district averages about 1–2 percent copper. On the basis of their metal content, the deposits are classified as vanadium-uranium deposits (V_2O_5 content greater than U_3O_8), copper-uranium deposits (more copper than U_3O_8), and uranium deposits (containing little or no vanadium or copper).

Ore deposits in the Cutler Formation in the Lisbon Valley area (fig. 4) are vanadium-uranium deposits having a $V_2O_5:U_3O_8$ ratio of 1:1 to 4:1; they contain small amounts of copper. Those in the Cutler in the Indian Creek area of the Moab and Monticello districts (pl. 1, loc. 12–22, 25–28, and 40–41) are uranium deposits with only minor amounts of vanadium and copper.

Deposits in the Chinle Formation have a wide range in their content of the three metals. Those in the Monument Valley district are mostly vanadium-uranium occurrences, although some along Oljeto Wash have more U_3O_8 than V_2O_5 (fig. 2). Some of the ores in this district contain a little copper. Most of the mineralized bodies in the White Canyon district are copper-uranium deposits, and the Cu : U_3O_8 ratio is as much as 13 : 1. Occurrences on the east side of the district, in the Elk Ridge area, have less copper, and many of them are classed as uranium deposits. An ill-defined but general increase in copper content westward through the district seems likely (fig. 3). In the Lisbon Valley area the deposits in the Chinle are either vanadium-uranium or uranium bodies; the vanadium content decreases markedly from the southeast end of the area to the northwest end (fig. 4). The copper content of these Chinle deposits is surprisingly low (about 0.00X percent), in view of the fact that copper minerals are visible in deposits in the underlying Cutler Formation and copper occurrences are numerous along the Lisbon Valley fault and associated fractures.

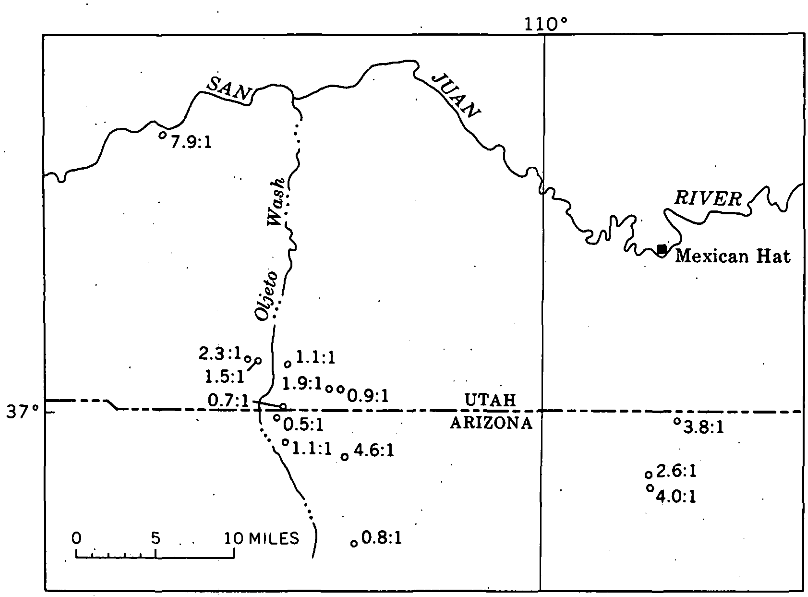

FIGURE 2.—V_2O_5 : U_3O_8 *ratios in ore deposits in the Shinarump Member of the Chinle Formation in the Monument Valley district, Utah and Arizona.* Not all the deposits shown on plate 1 are shown on this map, for the data on metal ratios are lacking for some deposits.

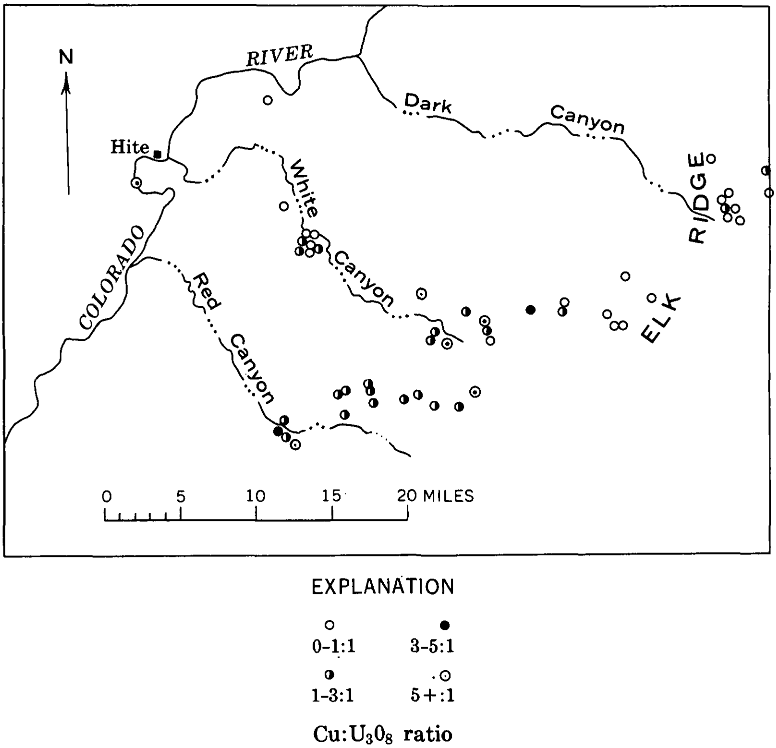

FIGURE 3.—Cu:U_3O_8 ratios in ore deposits of the White Canyon district, Utah. Not all the deposits shown on plate 1 are shown on this map, for the data on metal ratios are lacking for some deposits.

Virtually all the mineralized bodies in the Salt Wash Member of the Morrison Formation are vanadium-uranium deposits. The V_2O_5: U_3O_8 ratios range from 1:1 to 15:1. The several deposits in the Brushy Basin Member of the Morrison are classed as uranium deposits and have V_2O_5: U_3O_8 ratios of 1:2 or 1:3.

CONTROLS OF ORE

The known distribution and observed habits of the tabular uranium deposits in the region suggest that the localization of deposits is controlled mainly by sedimentary features. These may be gross features, such as the total lithologic characteristics or facies and the regional pinchouts of stratigraphic units; features of moderate scale, such as sandstone lenses and channel fills; and minor features, such as the presence of carbonaceous material (mainly fragments of fossil wood) and the detailed composition, texture, and structures of the mineralized sandstone. Tectonic structures do not obviously influence the

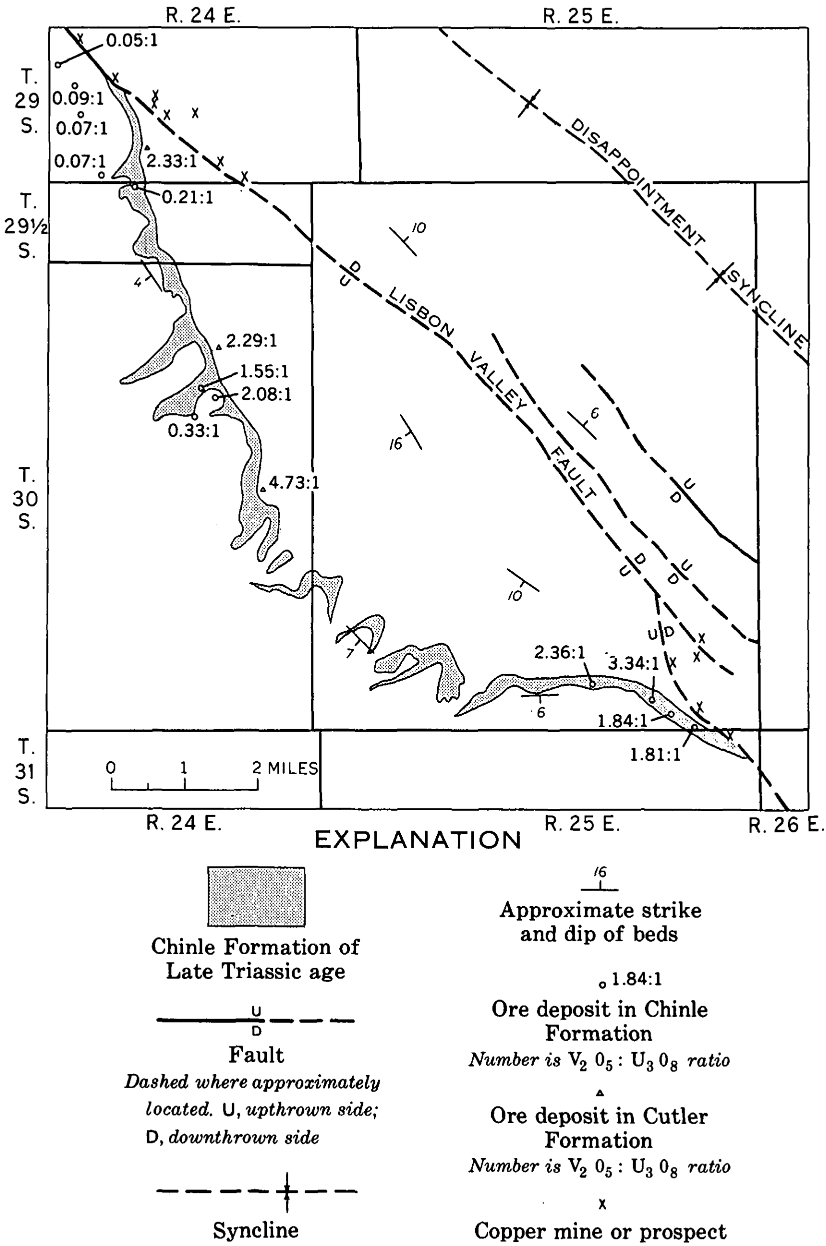

FIGURE 4.—V_2O_5:U_3O_8 ratios in ore deposits of the Lisbon Valley area, Monticello district, Utah. Not all the deposits shown on plate 1 are shown on this map, for the data on metal ratios are lacking for some deposits.

localization of the tabular deposits except as control on the distribution and lithologic characteristic of the host sandstone during deposition.

FAVORABLE SANDSTONE-MUDSTONE LITHOFACIES

The Salt Wash Member of the Morrison Formation was formed as a fan on a large alluvial plain (Craig and others, 1955, p. 137) and includes a conglomeratic sandstone facies, an intermediate sandstone and mudstone facies, and a claystone and lenticular sandstone facies (pl. 3). Uranium deposits are virtually confined to the intermediate sandstone and mudstone facies. Possibly the thick blanketlike beds of relatively clean sandstone in the conglomeratic sandstone facies allowed laterally moving ore-bearing solutions to be flushed easily through them and to be dispersed instead of concentrated. The claystone and lenticular sandstone facies is, in contrast, less permeable, and ore-bearing solutions probably could not pass through these rocks as freely as in the conglomeratic sandstone facies. The intermediate sandstone and mudstone facies may have provided optimum conditions for the localization of ore deposits—the sandstone lenses are sufficiently continuous to allow passage of large quantities of the ore-bearing solutions, and the interbedded less permeable mudstone would tend to confine the solutions in the sandstone. At any rate, the sandstone-mudstone facies of the Salt Wash Member seems to be a regional control of ground favorable for significant uranium deposits in southeast Utah and adjacent areas.

REGIONAL STRATIGRAPHIC PINCHOUTS

Regional pinchouts of ore-bearing units seem to be a large-scale control of ground favorable for significant uranium deposits in the Chinle Formation in the Moab, Monticello, White Canyon, and Monument Valley districts. In theory, any feature of the ore-bearing units that tends to restrict or concentrate laterally moving ore-bearing solutions might well be expected to influence the localization of ore. Regional pinchouts of these ore-bearing units could restrict or concentrate laterally moving solutions in two ways. First, there might be a damming of the solutions where permeable sandstones pinch out or interfinger with less permeable rocks. Second, near a regional pinchout otherwise blanketlike formations tend to become discontinuous, and laterally moving solutions probably concentrate in the few remaining thick sandstone lenses and channel-fill deposits. The larger ore deposits in the Shinarump and Moss Back Members of the Chinle Formation in the Moab, Monticello, White Canyon, and Monument Valley districts seem to be grouped within a few miles of the northeastern regional pinchouts of these units (pl. 1).

LOCAL PINCHOUTS AND FACIES CHANGES

Locally in the salt-anticline region of the Moab and Monticello districts the lower units of the Chinle Formation pinch out, thin, or change facies abruptly on the flanks of the Lisbon Valley, Moab, and Cane Creek anticlines. These structures apparently were positive areas during early Chinle time and influenced deposition of the lower part of the Chinle. The basal beds of the Chinle on the southwest flanks of the Lisbon Valley and Moab anticlines are coarser grained and more sandy than other beds of the Chinle, and these rocks seem to be preferred hosts for uranium deposits. Reconstructions of Chinle drainage patterns in the vicinity of these anticlines indicate that the main streams paralleled the long axes of the structures and suggest that these streams were deflected by the intermittently rising anticlines; possibly the coarser sandier rocks represent the traces of the main streams. It also seems possible, however, that the band of coarser sandier rocks is due in part to an influx of reworked sand from the Cutler Formation where it was exposed to erosion in the vicinity of salt anticlines at the beginning of Chinle deposition. A few minor streams did flow normal to the long axis of the Moab anticline; these suggest that there was some drainage down the flanks of the positive areas.

POST-MOENKOPI UNCONFORMITY

The Moenkopi-Chinle contact is unconformable throughout the Moab, Monticello, White Canyon, and Monument Valley districts. Along the crests and flanks of the salt anticlines where the Moenkopi was uplifted and eroded before Chinle deposition, the unconformity is conspicuously angular. In many other places channels were cut in, and locally through, the Moenkopi and were filled with basal sediments of the Chinle. Progressively younger Chinle beds overlie the Moenkopi from south to north.

Regardless of the stratigraphic unit that forms the basal part of the Chinle Formation, all or nearly all uranium deposits in the Chinle are within about 50 feet of the base of the formation. In Monument Valley and in Red and White Canyons in the White Canyon district the Shinarump Member is the basal unit of the Chinle and the deposits are in the basal part of the Shinarump. Just north of White Canyon the Shinarump is missing and the Monitor Butte Member is the basal unit and contains a few small deposits (pl. 1). Northwest of the White Canyon district, larger deposits occur in the lower part of the Monitor Butte in the San Rafael Swell (Johnson, 1957) and along the Dirty Devil River (Johnson, 1959b), where it is the basal unit of the Chinle. The Moss Back Member is at the base of the Chinle in the Lisbon Valley and Indian Creek areas and is ore bearing. A few miles northwest of Moab, in the Seven Mile area of the Green River district (Johnson, 1959b), uranium deposits occur in the basal beds of the Chinle, probably at a slightly higher stratigraphic level than the Moss Back Member. An illustration prepared by Stewart, Williams, Albee, and Raup (1959, fig. 81) to show these relations is reproduced herein as figure 5.

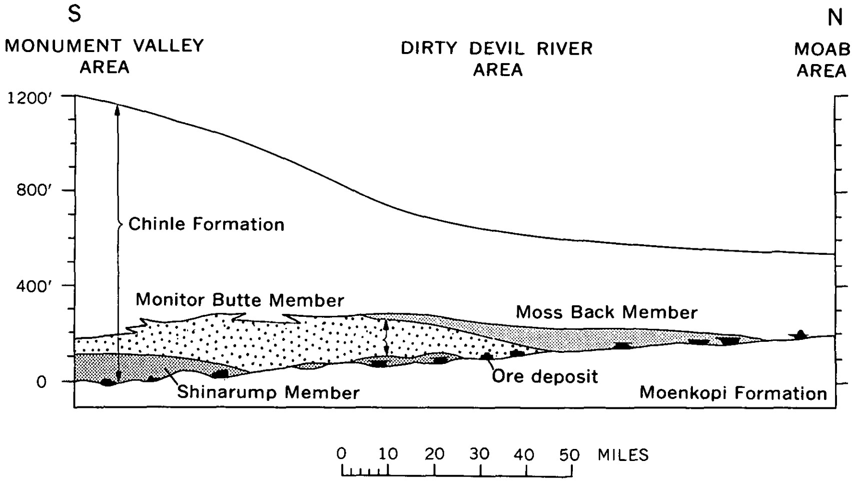

FIGURE 5.—Distribution of ore deposits in the Chinle Formation in southeast Utah. After Stewart, Williams, Albee, and Raup (1959).

SANDSTONE LENSES

Most of the ore-bearing sandstones in the Moab, Monticello, White Canyon, and Monument Valley districts are stream deposits. Many of these host standstones are conspicuously lenticular, especially in the Shinarump Member of the Chinle and the Salt Wash Member of the Morrison. These lenses were formed by sediments that either filled channels cut into the underlying beds or that laterally interfingered with finer grained sediments that accumulated on flood plains. Thicker than average sandstone lenses have long been noted as an apparent ore control for most uranium deposits on the Colorado Plateau (Coffin, 1921, p. 184; Weir, 1952, p. 26). The ore deposits are related to major or trunk channel systems, to characteristics of individual channel fills or lenses, and to the more favorable parts within lenses.

Known uranium deposits in the Shinarump Member of the Chinle in the White Canyon district, Utah, are virtually confined to sediments deposited in the ancient Elk Ridge-White Canyon channel system (pl. 1). Streams of this system flowed westward into the

White Canyon district, probably from a source in granitic terrane of the ancestral Uncompahgre Highland in southwest Colorado (Johnson and Thordarson, 1959). In the west-central part of the district, sediments deposited in this channel system interfinger with non-ore-bearing Shinarump deposited by northward-flowing streams. Lithologic and channel characteristics of the rocks derived from the Elk Ridge-White Canyon channel system apparently make these rocks more favorable hosts for uranium deposits than the Shinarump deposited by northward-flowing streams. In this respect, delineation of the Elk Ridge-White Canyon channel system outlines ground favorable for significant uranium deposits in the White Canyon district. The channel system may be considered a regional control of favorable ground within that part of southeast Utah.

At places the Salt Wash Member is thicker than average, contains a greater percentage of sandstone, and has sandstone lenses that are thicker than average. These accumulations of sandstone are interpreted as indicating the position of rather persistent trunk channel systems. They commonly contain clusters of ore deposits, and it is probable that trunk channel systems are one of the major controls of ground favorable for uranium deposits in the Salt Wash.

Sandstone-filled channels or scours cut into less permeable rocks are common loci for uranium deposits in the Chinle Formation, especially in the Shinarump Member (Wright, 1955, p. 140–142; Miller, 1955, p. 164; Witkind, 1956a). Most deposits are in the lower parts of these filled channels, and they are in irregularly bedded sandstone that contains pebbles and lenses of mudstone and fragments of fossil wood. It is commonly assumed that these channel fills provided better passageways for laterally moving ore solutions than did the surrounding, less permeable beds. The localization of deposits in the lower part of the channel fills is assumed to be due either to favorable textural and compositional characteristics of the host rocks in this part of the fill or to gravitational flow of ore-bearing solutions to the channel bottoms.

Some channels can be traced for several miles, whereas others become shallow and indistinguishable within a few hundred feet. The short channels may represent the deeper scours at the base of a larger wide shallow channel. Exploration along the trend of shorter channels then may lead to the discovery of similar short channels.

Many geologists have suggested that deeper scours might be expected to occur on bends in channels in the Shinarump and that bends are therefore more favorable for ore deposits than the straight stretches of the channels.

Channels are less obvious in the Salt Wash Member of the Morrison Formation than in Triassic rocks, and consequently the relation between uranium deposits and channels is less well defined in the Salt Wash. The thicker sandstones, in which the ore deposits tend to occur, probably were formed in the channel parts of large braided streams.

Stokes (1954, p. 47) suggested that ore deposits are more common on the bends of channels in the Salt Wash Member of the Morrison because more carbonaceous material was deposited there than along straight stretches of the streams. The authors' observations tend to substantiate this idea with regard to ore deposits in the Salt Wash. Yet the evidence is by no means conclusive.

CARBONACEOUS MATERIAL

Carbonaceous material in the form of carbonized wood fragments, leaves, or stems has long been recognized to be intimately associated with uranium on the Colorado Plateau (Boutwell, 1905, p. 209; Hess, 1914, p. 680; Weir, 1952, p. 22–23). Carbonaceous material in the host rock apparently helped to provide a reducing environment conducive to precipitation of uranium and other metals. Carbonaceous material alone may not have been a strong ore control, however, inasmuch as it is also common in barren rock either close to ore bodies or distant from known ore.

FAVORABLE HOST-ROCK LITHOLOGY

In the Shinarump Member of the Chinle Formation some channel-fill units contain uranium deposits whereas others only a short distance away are barren. All the ore-bearing rocks contain more carbonaceous material and interbedded mudstone than do the barren rocks. On Elk Ridge, channel-fill units of the Shinarump Member commonly consist of sandstone that is relatively clean in parts of the channel but which contains abundant carbonaceous material and interbedded mudstone in different parts of the same channel. Ore solutions left no visible trace when they passed through the clean sandstone, but they precipitated uranium and other metals when they entered the more favorable environment of interbedded sandstone and mudstone.

STRUCTURE

In general, the relation of known uranium deposits to regional folding in the Moab, Monticello, White Canyon, and Monument Valley districts does not suggest any direct structural control of the ore deposits. Ore deposits occur indiscriminately on the crests or flanks of major anticlines and in synclines. Exceptions to this generalization are the belt of favorable ground on the southwest flank of the Lisbon Valley anticline and the inferred favorable belt on the southwest flank of the Moab anticline; these belts are probably indirectly related to the salt structures because the sedimentation was influenced by the positive areas over these anticlines (p. H29).

Lewis and Campbell (1956, p. 70; 1965) presented evidence suggesting that a westward-trending structural trough was formed across the Elk Ridge area, San Juan County, Utah, after deposition of the Moenkopi Formation and before deposition of the Moss Back Member of the Chinle Formation. Deposition of the Shinarump Member of the Chinle in the Elk Ridge area was virtually confined to the area of this inferred structural trough. Inasmuch as the Shinarump is a favorable host for uranium deposits in this area, any structural feature which may have controlled its deposition could also be considered an indirect control of favorable ground.

Most uranium deposits in the Moab, Monticello, White Canyon, and Monument Valley districts seem to bear no relation to faults, large or small. Most faults even seem to be younger than the ore deposits, as for example those that displace ore bodies at the Rattlesnake mine in the Lisbon Valley area. Exceptions to this are the faults that definitely control ore in the Richardson Basin area (Redhead mine) and in the Cutler Formation on the northeast flank of the Cane Creek anticline (p. H23).

Isachsen and Evensen (1956, p. 275) suggested that faults and fractures in the Lisbon Valley area controlled ascending ore-bearing solutions by providing passageways. One objection to this hypothesis is that it fails to account for the great number of similar ore deposits on the Colorado Plateau that, so far as is known, are in no way associated with faults.

The vanadium-uranium deposit at the Monument 2 mine (Witkind and Thaden, 1963), Monument Valley district, Arizona, is in a sandstone lens of Shinarump that fills a channel cut into underlying rocks. The area is on the flank of a broad regional fold; the beds dip about 5° E., and the ore-bearing channel trends at an angle to the regional strike (fig. 6). Finnell (1957) suggested that the deposit may be controlled by sandstone brecciated by small en echelon strike-slip vertical faults along the channel. He further postulated that these faults provided access for ore solutions rising from a deep source. These faults (fig. 6) have a maximum lateral displacement of about 6 inches but little or no vertical displacement, and they are apparently due to stresses set up by resistance of the thicker channel sediments of the Shinarump to differential bedding-plane movement in the underlying unit. Possible objections to the hypothesis presented by Finnell are: (1) that the minor faults described by him would be expected to die out downward within a few tens of feet and therefore are unlikely passageways for ore solutions from depth, and (2) that the widespread occurrence of similar uranium deposits not characterized by the tectonic elements at the Monument 2 mine suggests the unimportance of these structural features as an ore control.

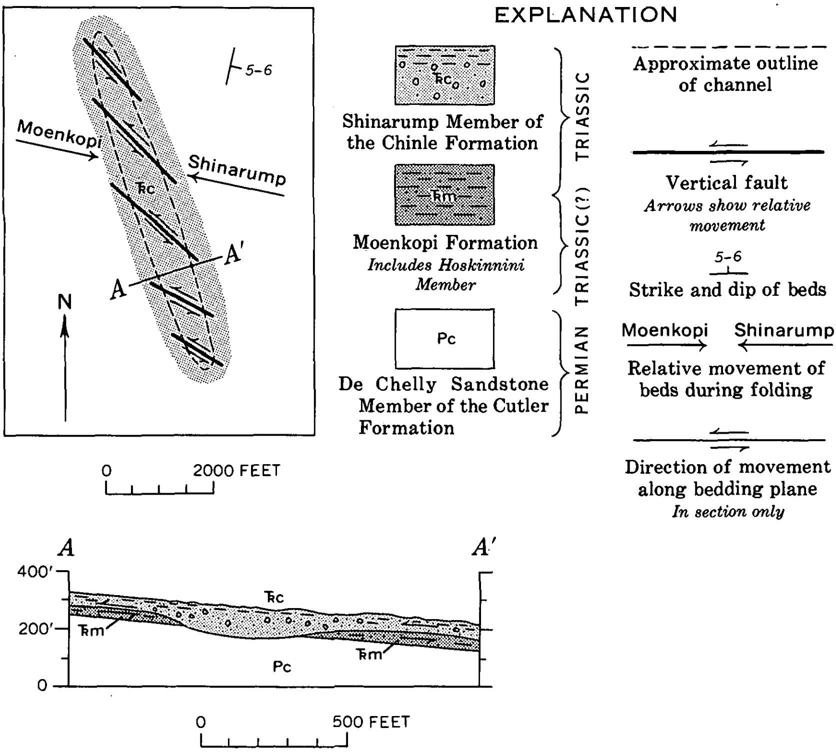

FIGURE 6.—Tectonic elements at the Monument 2 mine, Apache County, Ariz. After Finnell (1957).

GUIDES TO ORE

Some of the geologic features and relations described as controls of ore can be used in prospecting and in resource appraisal. These include: (1) regional pinchouts of the ore-bearing members of the Chinle Formation; (2) local pinchouts and facies changes in the basal parts of the Chinle along the flanks of salt anticlines that rose intermittently during Chinle time; (3) favorable beds in the lower part of the Chinle, within about 50 feet of the post-Moenkopi unconformity; (4) moderately thick sandstone lenses that fill channels or scours cut into underlying beds that are less permeable or are bordered by fine-grained flood-plain sediments; and (5) the lower parts of channels, or channel bends, where the channel-filling sandstone might contain more carbonaceous and shaly material and have irregular bedding due to local stream turbulence. Some of the tectonic structural features that have been discussed, and which locally may be a control for a deposit, are of questionable value as a general guide or in regional appraisal because of their limited distribution and limited association with ore. A few features that may be of some use in guiding exploration, but which were not mentioned above, are discussed in the following paragraphs.

In the Monument Valley district, Witkind (1956b; Witkind and Thaden, 1963, p. 80–81) pointed out that most ore-bearing channels are at the bottoms of broad gentle valleys or swales which are much larger targets for exploration than are individual channels. It was suggested that isopach maps of the Moenkopi Formation reflect these swales best and can be prepared easily by photogeologic methods.

According to R. Q. Lewis, Sr., (written commun., 1956) uranium deposits in the Monument Valley district have a crude halo of fluorescent silica (uraniferous hyalite and chalcedony) that coats fractures, joint surfaces, and shrinkage cracks in the surrounding rocks. The uranium content of the silica is responsible for the fluorescence and apparently varies inversely with the distance from ore. With a short-wave ultraviolet lamp, fluorescence can be observed in silica containing as little as 15 parts per million uranium. Apparently the uraniferous silica was distributed through the surrounding rocks during oxidation of the nearby uranium deposits, perhaps less than 35,000 years ago, according to Lewis. Consequently, fluorescent silica can be used as a guide only for oxidized deposits.

Several alteration effects are often useful guides to ore. Limonite and green and blue secondary copper minerals commonly form from oxidation at or near mineralized outcrops. The top few feet of a normally brown or reddish-brown unit immediately beneath the ore-bearing unit generally has been altered to gray-green, but the thickness of this alteration zone does not seem to be directly proportional to the intensity of mineralization in the ore-bearing unit. Brown or reddish-brown mudstone seams or lenses are usually altered to gray-green near ore deposits. Ore-bearing units are commonly light gray to buff near ore deposits but reddish-brown at some distance from ore. Where the ore-bearing unit is unoxidized, pyrite and copper sulfides are useful as an ore guide.

Bleached areas are common along fractures in reddish-brown rocks and are probably related to the passage of ground water or other solutions of unknown source. Uranium deposits are so rarely associated with this type of bleaching that it is not a guide to ore. Rather it seems to be indicative only of faulted and fractured rocks.

In calcareous host rocks, such as some parts of the Moss Back Member of the Chinle, uraninite may be accompanied by coarsely recrystallized calcite, some of which is replaced by chert. The chert and some of the calcite is colored orange or red by disseminated hematite. Although readily visible in mine workings and drill core, the recrystallized calcite and chert occur so close to uraninite blebs that these features probably are not practical ore guides.

ORIGIN

Uranium-, vanadium-, and copper-bearing deposits on the Colorado Plateau were probably formed during latest Cretaceous or early Tertiary time. According to Stieff, Stern, and Milkey (1953, p. 15), lead-uranium ratios indicate that these ores are about 65 million years old. Because the enclosing rocks are much older—the Morrison Formation is 130 million years old—it is evident that the ore metals were epigenetically introduced or redistributed.

The source of the metals in Colorado Plateau uranium deposits is not known. It may have been original material within the sediments, migrating uraniferous petroleum, or hypogene solutions.

Whatever their source, the metals apparently were deposited from solutions which traveled for the most part laterally through the rocks until confinement or favorable host rock caused precipitation of the ore minerals. The widespread occurrence of uranium, vanadium, and copper deposits on the Colorado Plateau suggests a general distribution of the ore-bearing solutions over large areas (tens of thousands of square miles). Local spots of bleached mineralized rock (commonly associated with carbonaceous material) surrounded by reddish-brown unmineralized rock suggest that ore-bearing solutions passed through some rock without bleaching or altering it in any visible way. On the other hand, iron, calcite, and silica have been leached from some parts of the rock and redeposited in other parts of the rock from a few inches to possibly thousands of feet away. From theoretical considerations (McKelvey and others, 1955, p. 506) and the iron content of sphalerite in the ores (Coleman, 1957), the temperature at which these deposits formed is inferred to be 55°–120°C.

The association of fissure veins of copper-silver ore (as at the Cashin mine) and less well-defined fault-controlled copper deposits (at the Big Indian mine) with tabular uranium-vanadium-copper deposits in southeast Utah and adjacent parts of southwest Colorado invites speculation that both types of deposits are part of a continuous sequence of mineralization. The mineralogical similarity of ores from the Cashin mine and copper-uranium deposits of the White Canyon district supports this view, even though silver is scant in the tabular deposits and uranium is sparse in the veins. On the other hand, it seems equally possible that the copper-bearing vein deposits were formed by solutions entirely different from those responsible for the tabular deposits. If they were, the copper-uranium deposits in the White Canyon district may represent local mingling of copper-bearing and uranium-bearing solutions. The rather common occurrence of copper minerals in faults associated with the collapse of salt anticlines (most of these faults are apparently younger than the tabular uranium deposits) supports the idea that these two types of deposits were formed by separate solutions.

Several workers (Reinhardt, 1952; Kerr, 1958; Weir and Puffett, 1960) have suggested that the igneous rocks of the Colorado Plateau (for example, the La Sal and Abajo Mountains) and the metals in the uranium deposits have a common source. The evidence for this relation is not yet conclusive, and the general distribution of uranium deposits on the Plateau does not seem to reflect any relation to these igneous rocks.

RELATIVE FAVORABILITY OF GROUND

The uranium deposits in this area tend to be concentrated in certain formations, and within these the deposits tend to be clustered in certain parts. Consideration of the geology of the districts and the habits and probable controls of the deposits aids in the delineation of inferred belts of more favorable ground and in resource appraisal.

The principal ore-bearing rocks are lenticular. In general the deposits are in the thicker, more permeable lenses where solution movement would have been greatest, but in detail many deposits are localized where the sandstone bedding is irregular and where the sandstone contains lenses of mudstone. The abundance of carbonaceous material in the mudstone-sandstone may have provided a chemical environment conducive to the precipitation of ore minerals.

Clean blanketlike sandstone beds that are lithologically uniform contain few deposits, perhaps because any ore-bearing solutions that passed through them were dispersed or did not enter a chemical environment favorable for ore deposition. Stratigraphic units that are dominantly argillaceous contain few if any deposits, perhaps because the chemical environment was not favorable or because the movement of solutions was inadequate.

Except for a few deposits along fractures, deposits were not obviously localized by tectonic structural features; there is no consistent association between deposits and tectonic features, although tectonic features may have influenced the original deposition of favorable sandstone beds.

A brief discussion of the relative favorability of each potentially ore-bearing unit within the Moab, Morticello, White Canyon, and Monument Valley districts is given below. Geology and ore potential of unexposed parts are, necessarily, extrapolated from the nearest areas where these units crop out.

PRE-HERMOSA FORMATIONS

Formations older than the Hermosa Formation of Middle and Late Pennsylvanian age are not exposed in the four districts. Accordingly, there is little evidence on which to appraise the uranium potential of these rocks. No lenticular fluvial sandstone similar to the principal known ore-bearing units on the Colorado Plateau is known in the pre-Hermosa rocks, and hence there is little chance of finding ore deposits like those in the Chinle or Morrison Formations. Ore deposits of other types might be present in unexposed rocks, but there is no evidence of their existence.

HERMOSA FORMATION

The Hermosa Formation is not known to contain significant ore-grade uranium deposits in the report area. Trace amounts of uranium are present in what is thought to be Hermosa at the Big Chance claims about 2 miles west-northwest of Moab (pl. 1). Weak and spotty occurrences of secondary copper minerals are known in the Hermosa where it crops out on the upthrown side of the Lisbon Valley fault. In oil wells between the Green and Colorado Rivers west of the Moab district, weak radioactivity has been noted in shale and limestone of the upper member of the Hermosa and in black shale of the Paradox Member.

If the uranium deposits of the Colorado Plateau were formed from hypogene solutions, limestone of the Hermosa Formation might conceivably provide a good host rock for ore, especially where fractured or brecciated in the vicinity of faults and sharp folds. Exposures of the Hermosa near the Moab and Lisbon Valley faults, and at least one drill hole near the Moab fault, however, show no mineralized rock or recrystallized limestone.

Mainly because the outcrops lack ore deposits, the Hermosa Formation is thought by the authors to have little potential for significant uranium deposits in this region.

RICO FORMATION

No uranium deposits of appreciable size and grade are known in the Rico Formation in the report area, but locally in the westernmost part of the Moab and Monticello districts (pl. 1) the Shafer limestone of former local usage and underlying red sandstone of the topmost part of the Rico contain secondary uranium minerals (Volgamore and deVergie, 1957, p. 10). These uranium occurrences may have been derived from weathering of small ore deposits in the overlying Cutler Formation.

The general lack of carbonaceous material and of bleaching in the purplish-red and brown Rico may indicate that it was a relatively unfavorable host for uranium deposits. Inasmuch as the Rico's fairly extensive outcrops lack significant uranium deposits, the authors consider the Rico to have little potential for uranium ore.

CUTLER FORMATION

The Cutler Formation contains many small uranium-copper deposits (commonly less than 100 tons in size and averaging about 0.15 percent U_3O_8 and less than 1.00 percent copper) in the westernmost part of the Moab and Monticello districts (pl. 1). These deposits are in small lenses of bleached white arkosic sandstone. Contacts between bleached and unbleached rock locally cut across bedding planes, and the bleaching was undoubtedly caused by solutions that moved laterally through the more permeable parts of the Cutler. The consistent association of bleaching and ore minerals suggests that the same solutions were responsible for both or that the metal-bearing solutions followed the path of earlier bleaching solutions. Carbonaceous material is not present in the Cutler in this area. Joints apparently were important in localizing ore and in providing entryways for the mineralizing and bleaching solutions into the permeable arkosic sandstone lenses. According to Volgamore and deVergie (1957), exploration of these deposits indicated a concentration of uranium in secondary minerals on the outcrop and an inward diminution of material of ore grade. Several similar, though larger, uranium and vanadium-uranium deposits are known in the Cutler Formation in the Lisbon Valley area of the Monticello district (pl. 1).

The tabular uranium-copper deposits just described are in the transition zone where the Cutler Formation changes from predominantly white eolian sandstone in the southwest to predominantly fluvial arkosic red beds in the northeast. Possibly the interfingering of the two facies formed stratigraphic traps which guided laterally moving ore-bearing solutions and permitted the precipitation of the ore minerals. The northwest-trending transition zone appears to be relatively favorable for low-grade uranium-copper deposits as large as a few hundred tons.

At the Monument 2 mine (Witkind and Thaden, 1963) in the Monument Valley district, vanadium-uranium ore occurs in the top few feet of the De Chelly Sandstone Member of the Cutler immediately beneath an ore deposit in the Shinarump Member of the Chinle. The ore in the De Chelly at this place is definitely related to the ore deposit in the Shinarump, and the De Chelly itself, a clean even-grained reddish-brown eolian sandstone, is therefore not considered favorable for uranium deposits elsewhere.

On the northeast flank of the Cane Creek anticline in T. 27 S., R. 21 E., Salt Lake meridian, in the Moab district, uranium ore deposits occur in minor faults in the Cutler Formation (pl. 1). In 1956, exploration had exposed a mineralized fault to a depth of about 200 feet, where the ore consisted of knife-edge veinlets of uraninite and some andersonite and asphaltic material. The sparseness of alteration phenomena in the wallrock of the veins and the absence of common vein-forming gangue minerals where the veins are exposed suggest formation of the uranium deposit from supergene solutions that derived the uranium from deposits in the Chinle Formation a few hundred feet above. If this postulation is correct, ore deposits in these faults and similar ones probably do not extend downward very far.

In view of the lack of ore deposits in outcrops, a general lack of interbedded lenticular sandstone and mudstone, and the absence of carbonaceous material, the Cutler Formation is not considered favorable for uranium deposits outside the relatively favorable zone of transition from white eolian sandstone to fluvial arkosic red beds in the Moab and Monticello districts.

MOENKOPI FORMATION

On The Notch 5 claim in the vicinity of The Notch in the Elk Ridge area of the White Canyon district, small amounts of uranium and copper occur in white to light-brown fine-grained sandstone about 40 feet below the top of the Moenkopi Formation. The ore minerals are intimately associated with heavy petroliferous residue that appears to be trapped in a small anticline. Immediately overlying the Moenkopi here, uranium-copper ore occurs in a channel filled with the Shinarump Member of the Chinle Formation. Perhaps ore-bearing solutions moving through the Shinarump descended along fractures into the Moenkopi where asphaltic material caused precipitation of uranium and copper minerals.

Except for the ore deposit described above, the Moenkopi Formation is not known to contain uranium in the four districts. The Moenkopi does contain fluvial sandstone lenses, however, and although carbonaceous material is generally absent, petroliferous residues are fairly common and conceivably caused precipitation of uranium ores in some places. The Moenkopi generally lacks ore deposits in its extensive outcrops and thus probably has little or no potential for uranium in the area.

CHINLE FORMATION

MOTTLED UNIT

Rocks of the mottled unit are not known to contain economic uranium deposits in the report area but may locally contain minor amounts of uranium disseminated in red chert layers, as thick as 1 foot, near the top of the unit. Uraninite(?), pyrite, chalcopyrite, chalcocite, covellite, galena, sphalerite, tetrahedrite(?) or tennantite(?), calcite, and yellow secondary uranium minerals, all occurring in small amounts, have been identified in similar radioactive red chert just west of the Moab district (C. C. Hawley, oral commun., 1956).

Inasmuch as the mottled unit lacks ore deposits in outcrops and also lacks carbonaceous material, it probably is unfavorable for uranium deposits and has no appreciable resource potential.

SHINARUMP MEMBER

The Shinarump Member of the Chinle Formation is the principal ore-bearing unit in the White Canyon and Monument Valley districts. It is absent from the Moab district, and it does not crop out in the Monticello district though it may be present at depth there. Ore deposits in the Shinarump are confined to units that fill channel scours cut in underlying beds. The larger ore deposits in the Shinarump in the White Canyon and Monument Valley districts contain more than 10,000 tons of ore and some contain more than 100,000 tons.

The Shinarump Member in the White Canyon district may be divided into (1) sediments that were deposited by westward-flowing streams which headed in granitic terrane of the ancestral Uncompahgre Highland in southwest Colorado and (2) sediments that were deposited by streams flowing northward from a southerly source. The westward-trending channel system (pl. 1)—named the Elk Ridge-White Canyon channel system (Johnson and Thordarson, 1959)—contains within its reconstructed boundaries all known economic uranium deposits of the White Canyon district. The sediments deposited in the Elk Ridge-White Canyon channel system contain abundant carbonaceous material and interbedded mudstone, and they apparently provided a more favorable environment than did sediments deposited by northward-flowing streams. The sediments deposited by northward-flowing streams in the southwest part of the White Canyon district are characteristically blanketlike sandstone beds having only minor amounts of carbonaceous material and interbedded mudstone.

Although all the Shinarump that fills channels within the reconstructed boundaries of the Elk Ridge-White Canyon channel system is considered favorable for uranium deposits, ore deposits are most likely to be found at those places where mudstone and carbonaceous material are abundant.

In the Monument Valley district the Shinarump Member seems to be divisible, according to channel trends and characteristics, into two channel systems roughly separated by a line parallel to and just east of the axis of the Organ Rock anticline (pl. 1). Data on channel characteristics presented by Witkind (1956a, p. 114) indicate that channels east of the dividing line trend northwestward and average about 170 feet in width and that channels to the west trend northward to northeastward and average about 490 feet in width. The widest channel east of the dividing line is about 700 feet wide, and the widest channel to the west is about 2,300 feet. Except for the Whirlwind mine, all known uranium deposits of economic size and grade in the Monument Valley district occur east of the dividing line.

Eastward from the Monument 2 mine area, and also along the trend of the Elk Ridge-White Canyon channel system eastward from the Elk Ridge area, the Shinarump probably contains uranium deposits larger than 10,000 tons; however, in both areas the Shinarump is covered by at least 1,000 feet of younger rocks. Hidden channels in the Monument Valley and White Canyon districts, especially in the Elk Ridge area of the White Canyon district, probably contain undiscovered ore deposits of more than 10,000 tons.

MONITOR BUTTE MEMBER

Several small uranium deposits are known in the Monitor Butte Member in the White Canyon district (pl. 1), but in 1956 these deposits had no appreciable economic significance. Most of these deposits are in small sandstone lenses as much as a few feet thick, but some are in sandy mudstone. The lack of thick sandstone lenses and the absence of passageways for uranium-bearing solutions probably are the reason for the absence of larger ore deposits.

All known uranium deposits in the Monitor Butte are within about 20 miles of its regional pinchout (pl. 1). The Monitor Butte thus seems most favorable near the regional pinchout. If the Monitor Butte contains thick sandstone lenses in the area within a few miles of the regional pinchout, it could conceivably be the host for fairly large uranium deposits in the White Canyon district. The Monitor Butte's potential for uranium resources is, however, not considered significant.

MOSS BACK MEMBER AND UNDIFFERENTIATED BASAL PART OF CHINLE

The Moss Back Member apparently contains significant uranium deposits only where it is the basal unit of the Chinle Formation in the Moab and Monticello districts (pl. 1). In these places it is much thinner and more lenticular than in the White Canyon district. The thin lenticular Moss Back, probably related to the regional pinchout of recognizable Moss Back (pl. 1), may have caused laterally moving ore solutions to be guided and confined. Where thick and blanketlike, the Moss Back probably caused laterally moving solutions to be dispersed.

In the Lisbon Valley area of the Monticello district large uranium deposits occur in greenish-gray sandstone, siltstone, and calcareous siltstone pebble conglomerate of the Moss Back Member. The ore deposits are apparently confined to a narrow belt, slightly more than half a mile wide, trending northwestward approximately parallel to the axis of the Lisbon Valley anticline (pl. 1). Orientation of shallow channel scours and elongate sandstone lenses suggests that the principal Chinle drainage in this immediate area also was northwestward parallel to the Lisbon Valley anticline positive area. The belt of large ore deposits parallels the Chinle drainage and probably is related to sandier sediments deposited by a large Chinle stream. Minor sandstone lenses are oriented normal to the anticline and may have been formed by streams flowing down the southwest flank of the positive area.

The belt of ground containing large ore deposits on the southwest flank of the Lisbon Valley anticline is displaced northeastward by the Lisbon Valley fault. On the northeast side of the fault the ore-bearing interval is at least 1,500 feet deep, and through 1956 it had not been tested there. If, as seems likely, the belt of ore-bearing ground is related to sedimentary features, which in turn were controlled by the ancestral anticline, the favorable ground may not extend farther north than the plunging nose of the anticline; nevertheless, it would not necessarily end abruptly at the fault.

North and northeast of the Lisbon Valley fault, which approximately coincides with the long axis of the Lisbon Valley anticline, the nearest exposures of the basal part of the Chinle are about 10 miles away in Lackey Basin on the south flank of the La Sal Mountains (pl. 1). In Lackey Basin the lower 100 feet or more of the Chinle is composed of conglomeratic quartzose grit and mottled purple, red, and white siltstone and sandstone which apparently is equivalent to the mottled unit (p. H11). No greenish-gray sandstone, siltstone, and calcareous siltstone pebble conglomerate like those characteristic of the ore-bearing unit of the Lisbon Valley area crop out in Lackey Basin.

Somewhere between the axis of the Lisbon Valley anticline and Lackey Basin, the Chinle loses the greenish-gray rocks. In this respect the Chinle of the Lisbon Valley area seems to be similar to that between the Moab anticline and the first exposures of the basal part of the Chinle a few miles up the Colorado River to the northeast of Moab. There too, all exposures of the Chinle northeast of the anticlinal axis are lacking in greenish-gray rocks typical of the Moss Back whereas these greenish-gray rocks are well represented on the southwest flank of the Moab anticline.

The Lisbon Valley and Moab anticlines (which rose intermittently during Triassic time) may have acted as barriers, keeping greenish-gray sediments of the Moss Back largely on the southwest side of the two anticlinal axes. By analogy to the Lisbon Valley area, the basal part of the Chinle on the southwest flank of the Moab anticline is also inferred to be favorable for significant uranium deposits. Exposures of the basal part of the Chinle are lacking here, however, and (through 1956) exploration on the southwest flank of the Moab anticline was insufficient to prove or disprove this inference.

PETRIFIED FOREST, OWL ROCK, AND CHURCH ROCK MEMBERS

The Petrified Forest, Owl Rock, and Church Rock Members of the Chinle Formation are not known to contain uranium deposits in the Moab, Monticello, White Canyon, and Monument Valley districts. Probably the claystone and siltstone of these units were relatively impermeable to laterally moving ore solutions, and favorable host rocks (that is, lenticular sandstone beds containing interbedded mudstone and carbonaceous material) are generally lacking. These four members are considered to have no appreciable uranium ore potential in the report area.

WINGATE, KAYENTA, AND NAVAJO FORMATIONS

Known deposits in the Wingate, Kayenta, and Navajo Formations in the four districts are confined to small fracture-controlled copper-uranium ore deposits in the Wingate in the Richardson Basin area of the Moab district (pl. 1) and to small spotty occurrences of copper disseminated in the Navajo Formation a few miles south of the Abajo Mountains. Just to the northeast of the Monticello district, at the Cashin mine, copper occurs in a fissure vein in the Wingate Sandstone (pl. 1).

Apparently the relatively clean massive sandstone of the Wingate, Kayenta, and Navajo Formations is somewhat favorable for fracture-controlled copper deposits and for small disseminated copper deposits of uncertain origin. Tabular uranium deposits are not known in these units, however, and the general absence of favorable host rocks suggests that such uranium deposits are not likely. The Wingate, Kayenta, and Navajo Formations probably have no appreciable potential uranium reserves in the report area.

CARMEL, ENTRADA, SUMMERVILLE, AND BLUFF FORMATIONS

The Carmel, Entrada, Summerville, and Bluff Formations are not known to contain ore deposits in the area considered in this report, but the Entrada and Bluff Sandstones, being lithologically similar to the Wingate and Navajo Sandstones, are probably somewhat favorable for small fracture-controlled copper deposits. The Carmel, Entrada, Summerville, and Bluff Formations, generally lacking favorable host rocks and having no known uranium deposits, probably contain no appreciable potential uranium resources.

MORRISON FORMATION

The Morrison Formation has been one of the two principal sources of uranium ore mined in the report area and undoubtedly contains appreciable potential reserves.

SALT WASH MEMBER

The Salt Wash Member is, in the report area, completely within the sandstone-mudstone facies of the Salt Wash fan (pl. 1) and therefore is relatively favorable for vanadium-uranium deposits. Significant ore deposits, however, are not evenly distributed through the Salt Wash but rather are clustered in eastward-trending belts of relatively favorable ground thought to represent the traces of ancient stream channels or channel systems on the Salt Wash fan. These belts (pl. 1) are as much as 2 miles wide; in them the Salt Wash has thicker lenses of sandstone, sandstone and mudstone beds that are more lenticular and intermixed, and larger and more abundant vanadium-uranium deposits. Some belts of favorable ground can be easily recognized on the outcrop because of their noticeably thicker sandstone lenses. Others are only vaguely defined and are hard to distinguish. Relative—not absolute—thickness of the sandstone lenses is an index to favorability of the ground for significant ore deposits. In an area characterized by sandstone lenses that are commonly less than 20 feet thick, a lens 30 feet thick or more would be relatively favorable for uranium deposits. In areas characterized by sandstone lenses that are commonly much thicker, any lens less than 50 feet thick might be relatively unfavorable. Nevertheless, the thicker sandstone lenses were deposited in ancient stream channels, and reconstructions of Salt Wash drainage patterns are useful in the outlining of ground relatively favorable for significant uranium deposits.

Uranium deposits outside the favorable belts shown on plate 1 are rarely more than a few hundred tons in size and commonly are much less. The larger ore deposits within the favorable belts are commonly 10,000 tons or more in size.

Probably some of the most favorable ground in the Salt Wash in southeastern Utah is along the easterly projection of two or three favorable belts passing through East Canyon in the Monticello district. Sedimentary trends in the Salt Wash in this part of Utah suggest that the streams responsible for these belts were deflected southeastward by the Lisbon Valley anticline positive area. The belts may connect with similar eastward-trending belts of favorable ground in the Slick Rock district of Colorado and the ground between East Canyon in the Monticello district and Summit Canyon in the Slick Rock district should have fairly large potential uranium reserves in deposits as big as several tens of thousands of tons. Depth to the Salt Wash Member along these trends is 600–800 feet.

On the basis of sedimentary trends and the location of known large ore deposits, a favorable belt similar to those described is inferred between the Rattlesnake mine area and the La Sal Creek area about 10 miles to the east. The Salt Wash Member within this favorable belt should have fairly large potential uranium reserves in deposits larger than 10,000 tons in size. Depth to the Salt Wash along this trend ranges from about 600 to more than 1,000 feet.

RECAPTURE MEMBER

The Recapture Member is represented in the report area by only the claystone and sandstone facies. Near the base of the member, sandstone lenses similar to those of the Salt Wash Member, but smaller and less continuous, contain small spotty occurrences of vanadium-uranium minerals in a few places in the southern part of the Monticello district. Larger deposits are known in the Recapture Member only in the sandstone facies and the conglomeratic sandstone facies, 75–100 miles southeast of the Monticello district.

Mainly because its extensive outcrops lack significant ore deposits, the Recapture is thought to contain no appreciable potential resources in the report area.

WESTWATER CANYON MEMBER

The Westwater Canyon Member contains several small scattered uranium deposits in the southernmost part of the Monticello district. Intermittent small-scale mining has resulted in appreciable production from one of these deposits (pl. 1, No. 148), but no production has been recorded from the others. Though somewhat similar to the Salt Wash, the Westwater Canyon contains smaller amounts of carbonaceous matter and intermixed mudstone, and therefore was probably a less favorable host rock for uranium deposits. Largely because of the general absence of significant uranium deposits in the extensive outcrops, the Westwater Canyon Member is thought to contain no appreciable potential uranium reserves.

BRUSHY BASIN MEMBER

In the report area, known uranium deposits in the Brushy Basin Member are confined to the southernmost part of the Monticello district (pl. 1). At several localities, uranium occurs in beds 1–2 feet thick of light-green to greenish-black tuffaceous mudstone and siltstone—probably deposited in ponds or small lakes—about 100 feet below the top of the member. Megascopic uranium minerals are not visible in the fresh rock, but yellow secondary uranium minerals form on weathered surfaces. The uranium content of the fresh rock apparently increases directly with increasing darkness of the rock. The dark color was originally attributed mainly to the presence of finely divided carbonaceous material, but analyses for carbonaceous material indicated that all the rock contains less than 0.5 percent organic carbon. According to E. B. Gross (oral commun., 1956) the uranium is present largely as microscopic blebs of coffinite along fractures and disseminated through the rock.

In many respects the uranium deposits in the Brushy Basin Member in the southernmost part of the Monticello district appear to be similar to uranium-bearing rock in the Brushy Basin near Green River, Utah (Johnson, 1959b, p. 98). Both groups of deposits are characteristically blanketlike, have areal extents of 1–100 acres, and average about 1 foot thick. The uranium-bearing rock is characteristically darker than most of the predominantly variegated Brushy Basin rocks and in some places is carbonaceous (the deposits near Green River, Utah, contain 1–2 percent organic carbon). The average grade of these rocks is commonly less than 0.10 percent U_3O_8 but in some deposits may be as high as 0.30 percent U_3O_8. Vanadium, molybdenum, copper, lead, and zinc may be present in trace to minor amounts not exceeding the uranium content of the rocks.

Uranium deposits of the type just described may be more widespread in the Brushy Basin Member than has generally been realized and may represent appreciable potential reserves of low-grade uranium ore and uranium-bearing rock.

BURRO CANYON AND DAKOTA FORMATIONS

Sandstone beds of the Burro Canyon and Dakota Formations are similar in many respects to the ore-bearing rocks in the Shinarump Member of the Chinle Formation and in the Salt Wash Member of the Morrison Formation. The Burro Canyon and Dakota, however, are not known to contain significant uranium deposits in the report area. Possibly the blanketlike sandstone beds of the Burro Canyon and Dakota dispersed, rather than concentrated, uranium-bearing solutions. More probably the lack of ore deposits in the Burro Canyon and Dakota Formations is due to some other factor, as yet undetermined. The lack of ore deposits in extensive outcrops suggests that the Burro Canyon and Dakota contain no appreciable potential uranium resources.

MANCOS SHALE

The Mancos Shale is not known to contain uranium deposits in southeast Utah. Probably this unit was relatively impermeable to ore-bearing solutions, and, because of its uniform lithology, tended to disperse rather than concentrate any solutions which entered it. Possibly other factors contributed to the lack of ore deposits in it. Mainly because there are no ore deposits in its extensive outcrops, the Mancos Shale is thought to contain no appreciable potential uranium resources.

RESERVES

The Chinle Formation has been the source of about 91 percent of approximately 9 million tons of uranium ore produced through 1963 from the combined Moab, Monticello, White Canyon, and Monument Valley districts. Indicated and inferred reserves for the four districts are estimated to be a little less than one-fourth of the production. About 99 percent of these reserves are in the Chinle.

The Morrison Formation (in particular the Salt Wash Member) has been the source of most of the remainder of the ore produced from the four districts through 1963 and contains most of the reserves in the region that are not in the Chinle.

Potential uranium reserves in the Chinle in the four districts are thought to be from one to one-and-a-half times combined production plus indicated and inferred reserves as of January 1, 1964. Potential reserves in the Morrison Formation are thought to be from as little as two times to many times the several hundred thousand tons of combined production plus indicated and inferred reserves as of January 1, 1964. From 50 to 90 percent of the potential reserves are thought to be in the Chinle Formation and most of the remainder in the Morrison Formation.

Potential reserves in the Chinle Formation are virtually limited to large hidden ore deposits (several hundred thousand tons in size) that are likely to be present in the lowermost part of the formation in inferred belts of favorable ground (1) on the southwest flanks of the Lisbon Valley and Moab anticlines, (2) within the reconstructed boundaries of the Elk Ridge-White Canyon channel system and its buried eastern extension, (3) east of the Monument 2 mine area in the Monument Valley district, and (4) in the area of relatively discontinuous Moss Back within a few miles of the Moss Back's northeastern regional pinchout. Outside these favorable areas, ore deposits in the Chinle are probably so small and scattered as to contain no appreciable potential reserves.

The Morrison Formation's potential reserves are mostly in the Salt Wash Member, in ore deposits 1,000 to several tens of thousands of tons in size. These ore deposits are virtually confined to belts of relatively favorable ground coextensive with the trace of ancient channels on the Salt Wash alluvial plain. Outside these favorable belts, ore deposits in the Salt Wash are thought to be so small and scattered as to contain no appreciable potential reserves.

The presence of uranium deposits 1,000–10,000 tons or more in size in the Brushy Basin Member of the Morrison in the Monticello district indicates that the Brushy Basin may contain appreciable potential reserves of low-grade ore and subore-grade uranium-bearing rock.

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