Geology, Altered Rocks And Ore Deposits of The San Rafael Swell Emery County, Utah

By C. C. HAWLEY, R. C. ROBECK, *and* H. B. DYER

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A study of the stratigraphy, structure, alteration, and uraniferous deposits in sedimentary rocks, with emphasis on the Chinle Formation

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CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

GEOLOGY, ALTERED ROCKS, AND ORE DEPOSITS OF THE SAN RAFAEL SWELL, EMERY COUNTY, UTAH

By C. C. HAWLEY, R. C. ROBECK, and H. B. DYER

ABSTRACT

The San Rafael Swell is a large asymmetric anticline in which sedimentary rocks ranging in age from Pennsylvanian to Cretaceous are exposed. The swell is a breached structural feature: its inner part, known as the Sinbad Country, is underlain mainly by rocks of Permian and Triassic age; the outer part, called the Reef, is formed mainly of resistant sandstone of the Glen Canyon Group of Triassic and Jurassic age. The Carmel Formation of Middle and Late Jurassic age and younger strata are exposed outside the Reef and are discussed only briefly in this report.

The oldest rocks exposed in the San Rafael Swell crop out in the deep canyons of Straight Wash and the San Rafael River; they are probably of Early Permian and Pennsylvanian age. Younger strata are exposed more extensively and consist of the Coconino Sandstone and Kaibab Limestone of Utah of Permian age, the Moenkopi Formation of Early and Middle(?) Triassic age, the Chinle Formation of Late Triassic age, and the Glen Canyon Group of Triassic and Jurassic age which contains the Wingate Sandstone, the Kayenta Formation, and the Navajo Sandstone.

The Coconino and Kaibab Formations are widely exposed in the east-central part of the swell. Their correlation with the type sections of these formations in northern Arizona is now regarded as very tenuous. The Moenkopi Formation underlies most of the Sinbad Country; it ranges from slightly less than 500 feet to more than 800 feet in thickness and is thinnest in a northwest-trending belt near Straight Wash on the east flank of the swell. The formation can be divided into three units: a lower part consisting largely of siltstone and subordinately of fine-grained sandstone, thin-bedded carbonates, and a basal chert-pebble conglomerate; the medial Sinbad Limestone Member; and a siltstone-rich upper unit, which contains thin sandstone beds. The Moenkopi Formation is overlain with probable slight angular unconformity by the Chinle Formation.

The Chinle Formation consists of four members: the Temple Mountain, Monitor Butte, Moss Back, and Church Rock. It crops out as a thin belt just inside the Reef and as erosional remnants in the Sinbad Country. The formation ranges from about 215 to 370 feet in thickness and is thinnest on the southwest flank of the swell. The Monitor Butte Member is the basal unit of the formation in the southern part of the swell, and the Temple Mountain Member is the basal unit in the northern part; they intergrade in the central part to form a thin basal unit. The Temple Mountain, Monitor Butte, and Church Rock Members are predominantly varicolored siltstone which was probably deposited on flood plains

and in shallow lakes; the Moss Back Member, largely light-colored sandstone, was deposited by a great northwest-flowing river system.

Southwest of a line drawn from a point south of Temple Mountain to Green Vein Mesa, the thickness of the Moss Back Member is locally variable because the member fills ancient channels cut into the Monitor Butte or Temple Mountain Member and, rarely, into the Moenkopi Formation. Northeast of this line the thickness of the Moss Back is more uniform, and the Moss Back is a blanketlike deposit. Local channels, however, are present in the Moss Back in the northern part of the swell near Calf Mesa.

The Wingate Sandstone overlies the Chinle with apparent conformity but with a marked break in lithology. The Wingate is almost entirely fine-grained white to pale-orange sandstone deposited in large-scale crossbeds. It is succeeded by the Kayenta Formation, characterized by interlayered strata of light-colored sandstone and siltstone.

Several thin discontinuous igneous dikes of analcite-biotite diabase of Tertiary(?) age crop out in the southwestern part of the swell and are part of a more extensive group of dikes and sills exposed about 4 miles west of the Chinle outcrop belt. The dikes are slightly radioactive and locally contain as much as 0.006 percent equivalent uranium. Indirect evidence of igneous activity is perhaps shown by several warm springs that issue from the Kaibab-Moenkopi contact in the northern part of the swell; these springs show slightly abnormal radioactivity.

The sedimentary rocks of the San Rafael Swell were folded probably in earliest Tertiary time into a great asymmetric doubly plunging anticline. The major axis of the anticline, from south to north, first trends north-northeast, swings abruptly east-northeast in the central part of the swell, thence north-northeast. Rocks on the west flank of the anticline dip 2°–5° W. To the east toward the Reef, the dip gradually increases before steepening abruptly near the Reef in a great monoclinal fold with moderately to steeply dipping beds. Associated structural features are small crossfolds. The present San Rafael anticline masks northwest-trending folds formed in Permian (?) and Triassic (?) time.

Pipelike collapse structures of probable solution origin are on the east flank of the swell near Temple Mountain, on the west flank near Reds Canyon, and in the northern part of the swell near Window Blind Butte. The collapses are crudely circular masses of altered rocks which have been downwarped or downfaulted into stratigraphically lower rocks. The collapse structures near Temple Mountain involve at least the Moenkopi, Chinle, and Wingate Formations, and at least one of the Red Canyon collapse structures bottoms on or below the Coconino Sandstone. The collapses show a close relation to small folds and probably formed in the same period as upfolding of the swell. Six of the collapse structures are locally slightly uraniferous, but only the main Temple Mountain collapse structure appears to contain an appreciable amount of uraniferous rock.

Bedding-plane and related faults of minor displacement occur near the Moenkopi-Chinle contact. Although of minor structural importance, these fractures are of premineralization age and they controlled some alteration and ore deposition.

Numerous high-angle faults mainly of postore age cut the sedimentary rocks. The faults belong to several sets; most have normal displacements, but a few are reverse faults. High-angle faulting probably started about the time of folding in earliest Tertiary time but reached maximum proportions later in the Tertiary. A few faults may be older than early Tertiary.

The rocks of the Moenkopi Formation, the Monitor Butte and Temple Mountain Members of the Chinle Formation, and the Glen Canyon Group were altered regionally. The Moenkopi Formation is altered in a wide belt which trends north-northwest across the north-central part of the swell. Although the alteration was partly stratigraphically controlled, the alteration boundaries are generally crosscutting. The alteration, which involved bleaching, pyritization, and introduction of oil, paralleled an anticline transverse to the present San Rafael anticline. It was probably caused by oil and associated connate fluids migrating into the old transverse anticline. In contrast to the crosscutting relation of most of the altered rocks of the Moenkopi Formation, the Monitor Butte and Temple Mountain Members and the uppermost part of the Moenkopi Formation are characteristically altered in nearly strata-bound zones. In this alteration, mottled purple-white (pale-green) rock was formed from original or diagenetic red rock. Jasperoid was formed abundantly in the most intensely altered rocks, along with small concentrations of kaolinite, barite, uraniferous asphaltite, and sulfides. Except at Temple Mountain, most uranium deposits occur in sandstone lenses or channels near the stratigraphic position of these altered zones. The Glen Canyon Group was pervasively bleached in the structurally higher parts of the San Rafael anticline; this zone of regional alteration is continuous with a similar, but more intensely altered zone of the same rocks in the Temple Mountain district.

Because of its control by an old anticline and its lack of correlation with uranium deposits, the alteration of the Moenkopi Formation is mainly believed to have predated the folding of the San Rafael anticline and also the deposition of uranium in the Chinle Formation. But, because folding of the San Rafael anticline renewed fluid movement, similar alteration could have also occurred later than the main period of Moenkopi alteration. The alteration of the Temple Mountain and Monitor Butte Members is difficult to date, but most probably it happened during folding of the San Rafael anticline. The alteration was synchronous with some uranium deposition. The occurrence of bleached Glen Canyon Group in the structurally higher parts of the anticline shows that this alteration took place during the late stages of or after folding of the anticline; this alteration probably took place at the time of ore deposition at Temple Mountain.

The uranium deposits of the San Rafael Swell occur principally in the three areas termed the South, North, and Temple Mountain mineral belts. The Temple Mountain belt lies wholly within the swell, but the other two belts probably continue in a northwest-southeast direction into the deeply buried rocks on the flanks of the swell. The northern boundary of the South belt is inferred to cross the swell from a point not far south of Temple Mountain on the southeast flank of the swell to Green Vein Mesa on the southwest flank; its southern boundary is buried. The South belt includes the Delta, Cistern, Little Erma, Little Susan, Dirty Devil, Conrad, and Lucky Strike mines, and the mines on Green Vein Mesa. The uranium deposits occur mostly in the Monitor Butte and Moss Back Members of the Chinle Formation. The North belt, which is less well defined, includes deposits in the Moss Back Member at Calf Mesa and numerous occurrences of mineralized rock in the Temple Mountain Member of the northern swell. The Temple Mountain belt parallels the local structure of the swell near Temple Mountain and can be traced for less than 2 miles. The ore in this belt is in the Moss Back Member of the Chinle Formation.

The South belt coincides with the part of the Moss Back Member that contains large scour-and-fill channel structures; it lies southwest of a near pinchout of the basal units of the Chinle Formation on the southwest flank of the old transverse

anticline. The belt is charactertized by purple-white altered Chinle. The North belt coincides with an area of local Moss Back channels and relatively thick, generally altered, Temple Mountain Member, that lies on the northeast flank of the transverse anticline.

Uranium deposits in the South mineral belt are mostly tabular ore bodies that are localized in isolated "scours" in channels of the Moss Back Member and in lenticular sandstone bodies of the Monitor Butte Member. The ore bodies are spotty in distribution and, with the exception of the Delta mine, contained less than 12,000 tons of ore with most ore bodies containing less than 4,000 tons. Grade of deposits was variable but generally rather low and averaged about 0.20 percent U_3O_8. The largest known ore body of the South belt, the Delta ore body, was about 600 feet long, as much as 500 feet wide, and 20 feet thick. The largest ore body in the Dirty Devil 4 mine, which is representative of several intermediate-sized mines, was about 120 feet long, 80 feet wide, and as much as 8 feet thick.

Deposits in the North belt are smaller and are found in channels in the Moss Back Member or in the Temple Mountain Member. Ore at the Dexter 7 was rather unusual in occurrence—the ore was found in two stratigraphic horizons in the lower part of the Moss Back in small roll and tabular bodies and also in small vertical pipes.

The major ore bodies of the Temple Mountain district differ from most other ore bodies of the swell by being partly roll-like in character, as well as by generally occurring above the basal unit of the Moss Back Member.

Most ore deposits were localized by channel structures, small-scale sedimentary structures, and bedding-plane and related low-angle slips that are common at or near sandstone-mudstone contacts. Small crosscutting deposits were localized by collapse structures and possibly on a very local scale by high-angle joints and faults.

The deposits formed by filling pores, and by replacement of interstitial cement, carbonaceous material, and, more rarely, detrital grains and are mainly composed of unoxidized minerals or mineraloids. The uranium is mainly contained in the mineraloid commonly termed asphaltite and in uraninite. Oxidized minerals of high-valent uranium are locally abundant. Small amounts of chalcopyrite, galena, sphalerite, chalcocite(?), molybdenite(?), montroseite, and other unoxidized metallic minerals accompany the uraninite or asphaltite. The oxidation of the sulfide minerals has produced marked concentrations of sulfate minerals near some of the mines, Cobalt and iron sulfate blooms are common near the mines of the Green Vein and Calf Mesa areas, respectively.

The metal content of deposits shows areal variations and to some extent stratigraphic variations; tentatively the deposits may be classified on the basis of the dominant metals and the distinctive metals (in parentheses) as follows: Vanadium-uranium deposits; zinc-(lead)-uranium deposits; copper-uranium deposits; and copper-(rare earth)-uranium deposits. The vanadium-uranium deposits are mainly at Temple Mountain; these are the only highly seleniferous deposits of the swell. Zinc-(lead)-uranium deposits are represented by a belt of deposits on the southwest side of the swell, and copper-uranium deposits, by Green Vein Mesa and Cistern mine ores. Copper-rich mineralized rocks that contain appreciable amounts of rare earths are mainly in the purple-white rocks in the Temple Mountain Member but are also rarely found in small deposits in the Moss Back Member. The Delta ore body was relatively copper-rich in the north part and lead-rich in the south. Other metals relatively abundant in the copper-rich ores are cobalt, nickel, and barium; molybdenum concentration seems to be highest in the zinc-rich ores.

INTRODUCTION

Sedimentary rocks of Pennsylvanian(?) to Cretaceous age are exposed in and near the San Rafael Swell, a great doubly plunging asymmetric anticline in Emery County, Utah (fig. 1). The Pennsylvanian(?) and Permian rocks are exposed in the southern and eastern parts of the area and form an irregular core for the progressively younger rocks of Triassic, Jurassic, and Cretaceous age (fig. 2). This report deals mainly with the rocks of Triassic age and the uranium deposits that they contain. The uranium deposits range in size from a few tons to more than 100,000 tons. All the main deposits of the swell are in either the Monitor Butte or the Moss Back Member of the Chinle Formation of Late Triassic age, but a few small deposits are found in other units or in collapse structures which can involve several formations. A few igneous dikes of probable Tertiary age are exposed on the southwest flank of the swell (fig. 2). The anticline is elongated in a northeasterly direction and is bounded on its east side by a great

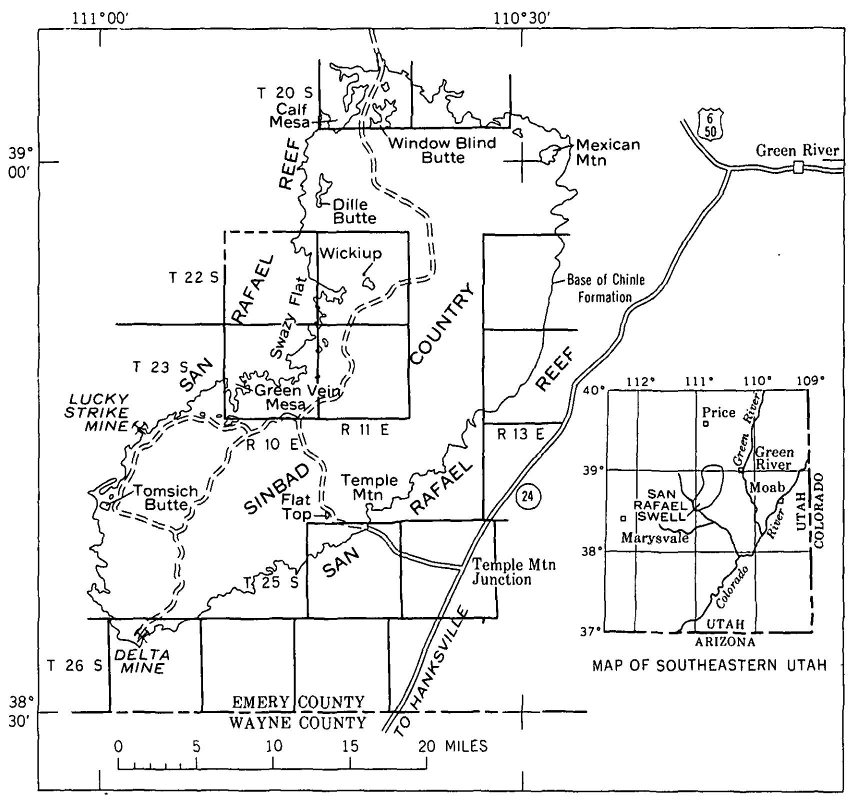

FIGURE 1.—Index map of the San Rafael Swell, Utah.

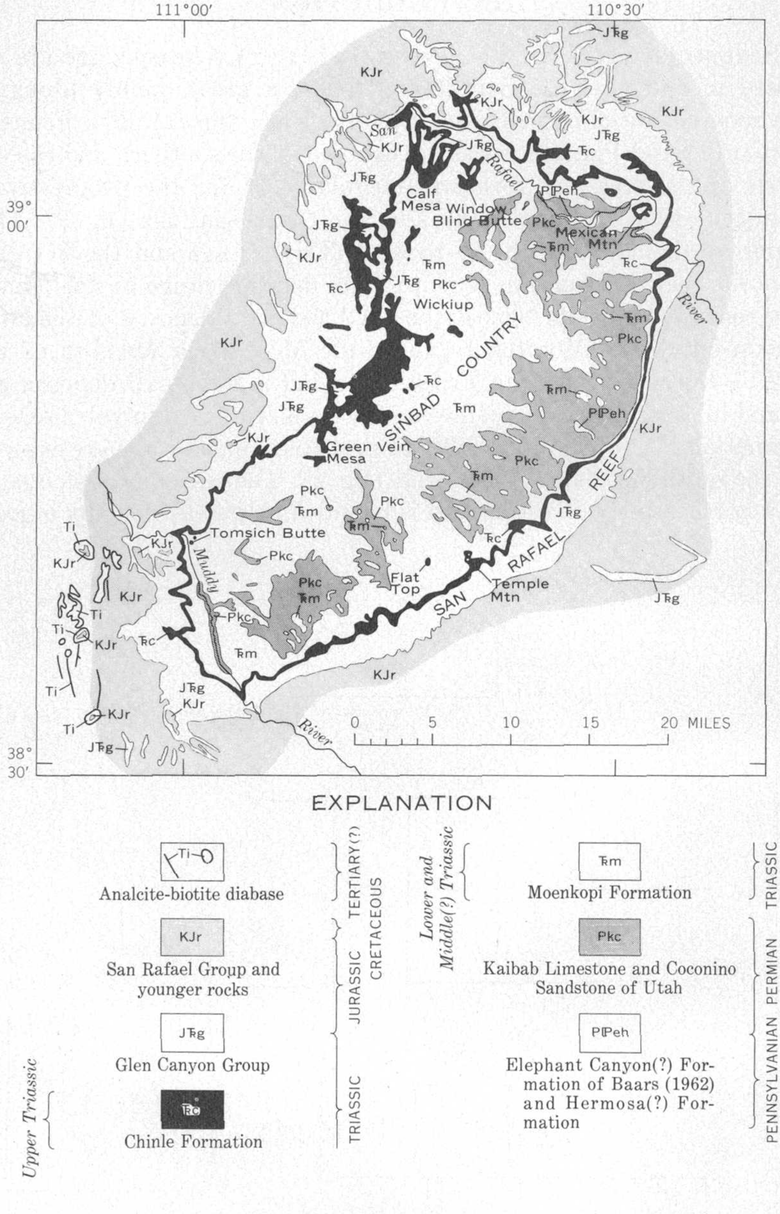

FIGURE 2.—Geologic map showing general distribution of major rock units in and near the San Rafael Swell. Modified from Andrews and Hunt (1948).

monoclinal fold. The present San Rafael anticline masks a minor older northwest-trending anticline. In turn, the present fold is modified by cross warps, many normal and a few reverse faults, and, locally, collapse structures. Altered rocks are also discussed because the ore-bearing rocks have been altered near the uranium deposits and because strata belonging principally to the Moenkopi Formation and the Glen Canyon Group have been altered on a regional scale.

This report is complementary to a report on the Temple Mountain district on the southeast flank of the San Rafael Swell (Hawley and others, 1965). The uranium deposits in the Morrison Formation of Jurassic age exposed on the flanks of the swell were beyond the scope of this investigation.

LOCATION AND GEOGRAPHY

The San Rafael Swell, a rugged and still rather inaccessible area, is in Emery County, Utah (fig. 1). The part of the swell near Temple Mountain can be reached by a paved road leading west from Temple Mountain Junction on Utah Highway 24, and relatively good gravel roads cross the central part of the swell and extend north to a gravel road between Castledale and Woodside. Other roads (some of which are shown on pl. 1 and in fig. 1) furnish access to the mining areas. It is always advisable to ask at Green River, Temple Mountain Junction, or at mining camps about the condition of roads within the swell. Extra water, food, and gasoline should always be carried. The location of mines and prospects is shown on plate 1. Because this report emphasizes uranium deposits, some geologic features discussed in the text are located with reference to mines or prospects; this enables the use of plate 1 as an auxiliary index map.

The geography of the area reflects the general geologic structure of the San Rafael Swell—a huge asymmetric domal anticline elongate in a northeast direction—and the variable resistance to erosion of the different sedimentary rocks. The anticline has been breached by erosion, and the central part, called Sinbad Country, is in most places an area of low relief. The outer part, called the Reef, is a steep ridge composed of the sandstones of the Glen Canyon Group. In most places between Sinbad Country and the Reef is a bench formed by resistant sandstones of the Chinle Formation.

SOME PREVIOUS GEOLOGIC INVESTIGATIONS

The general geology of various parts of the San Rafael Swell has been described by Gilluly (1929), Baker (1946), and Hunt, Averitt, and Miller (1953); earlier investigations of the swell are cited in papers by these workers. Recent revisions of the correlation of Triassic rocks in southeastern Utah, including revision of the nomenclature of the Chinle Formation ore-bearing units, are discussed by Stewart (1957).

The geology of the uranium deposits has been the subject of much investigation; however, many reports are unpublished or have little general distribution. The literature on the Temple Mountain district is extensive and is summarized in the report on that district (Hawley and others, 1965); more important published papers on the Temple Mountain district include those by Keys and White (1956) and Kerr, Bodine, Kelley and Keys (1957).

The Delta mine has been described by Keys (1954), and other mines and mine areas have been described by other U.S. Atomic Energy Commission or Geological Survey geologists as noted in the mine and area descriptions.

Reports on reconnaissance investigations of uranium deposits were made by Gott and Erickson (1952) on the occurrence and origin of the asphaltite-bearing ores and by Johnson (1957) on the potential uranium resources of the swell. Finch (1953a, b, 1959) proposed that the major uranium deposits in the southern part of the San Rafael Swell were in an east-trending belt which extended under the Green River Desert into the Moab area. An alternate interpretation favored by McKeown and Orkild (1958) and by us is that most of the deposits in the southern San Rafael Swell belong in a northwest-trending belt which projects toward the Orange Cliffs area.

Alteration features of regional extent in the San Rafael Swell or nearby Green River Desert–Orange Cliffs area were observed by Finch (1953a, b, 1959), McKeown and Hawley (1955, 1956), McKeown, Orkild, and Hallagan (1956), and McKeown and Orkild (1958). In a brief summary of investigations in the San Rafael Swell, Hawley (1958) described the regional alteration of the Moenkopi Formation, the lower part of the Chinle Formation (Monitor Butte and Temple Mountain Members), and the Glen Canyon Group.

The varicolored rocks of the lower part of the Chinle Formation and locally the uppermost part of the Moenkopi were first specifically discussed as an alteration feature by Finch (1953a, b). He termed the alteration zone the purple-white band; geologists of the Atomic Energy Commission generally termed similar rocks the "pinto zone" (Keys and White, 1956, p. 287). Finch (1959) and Schultz (1963), in a general discussion of the clay mineralogy of the Triassic rocks, proposed that the altered zone is a fossil-weathering zone. Other geologists, including Abdel-Gawad and Kerr (1963), believe it to be a zone of alteration related in some way to the uranium deposits.

SOURCES OF DATA AND ACKNOWLEDGMENTS

Most of this report is based on recent work by the Geological Survey. For information on certain areas, however, we have drawn extensively on published and unpublished reports of the U.S. Atomic Energy Commission. All the work has been done on behalf of the Division of Raw Materials, U.S. Atomic Energy Commission. Rock colors are from the National Research Council "Rock-Color Chart" (Goddard and others, 1948).

Studies were made by several groups of Survey geologists. Mapping parties consisting of I. J. Witkind, R. C. Robeck, and W. A. Barton in 1953 and of R. C. Robeck and H. B. Dyer in 1954–55, assisted by G. A. Izett, R. W. Thompson, B. R. Doe, and J. W. Richards, studied the Temple Mountain and Green Vein Mesa areas and their mines; they also mapped the rocks and desposits in the Chinle outcrop belts in the southwestern and northern parts of the swell. Studies were made in more detail at Temple Mountain, the Delta mine, and Tomsich Butte in 1956, by C. C. Hawley, J. G. Moore, J. A. MacKallor, and D. B. Brooks.

Topical studies by other Survey groups furnished much information to the San Rafael project. Data on the Lucky Strike mine were given to us by W. I. Finch; these data were obtained during a general study of the uranium deposits in Triassic rocks of the Colorado Plateau (Finch, 1959, 1967), but have not been previously published. The results of studies of the Triassic stratigraphy of the Plateau by J. H. Stewart, F. G. Poole, R. F. Wilson, and others served as a general guide in mapping the Triassic rocks within the swell.

Besides data gathered from formal reports of the U.S. Atomic Energy Commission, we have gained much from discussions of plateau geology with H. B. Wood, R. G. Young, and the geologists formerly of the Sinbad Field Camp of the U.S. Atomic Energy Commission: Gerald Chase, P. H. Dobbs, Ben Patterson, and R. L. White. We are also indebted to mine owners and mining men throughout the swell area and particularly to Jess Abernathy, John Motica, John Herron, and Gordon Irvine, Jr., of the Union Carbide Nuclear Corp., to Ray Schultze and John R. Mullen of the Hidden Splendor Mining Co., and to William Hannert, formerly associated with the Dirty Devil group of mines.

Hawley was responsible for nearly all the final preparation of text and maps for this report, for both Robeck and Dyer left the San Rafael project in 1956. Because of this, he accepts responsibility for controversial interpretations of data. He also wishes, however, to dedicate any especially worthy aspects of this report to a fine geologist, his friend and coauthor, the late H. B. Dyer.

STRATIGRAPHY

PRE-TRIASSIC ROCKS

Rocks of Pennsylvanian and Permian age are exposed below the Moenkopi Formation of Triassic age in parts of the San Rafael Swell, and oil tests show that sedimentary rocks of Pennsylvanian, Mississippian, Devonian, and Cambrian age lie between the base of the Pennsylvanian and the basement complex.

The oldest rocks exposed probably belong to the Lower Permian Elephant Canyon Formation of Baars (1962) and possibly include the uppermost part of the Pennsylvanian Hermosa Formation. These rocks are exposed in Straight Wash in sec. 19, T. 23 S., R. 13 E., and consist of, from base to top, about 100 feet of massive locally cherty finely crystalline limestone and dolomite and 260 feet of interbedded sandstone and carbonate rocks. They are overlain by more than 500 feet of flat and crossbedded sandstone that belongs to the Coconino Sandstone (Gilluly and Reeside, 1928, p. 63). An interval about 50 feet thick below the Coconino consists of interbedded tan-weathering limestone and crossbedded sandstone and appears to be transitional between the Elephant Canyon (?) Formation and the Coconino. Similar rocks form the base of the Coconino Sandstone in the Black Box (canyon) of the San Rafael River near the crest of the San Rafael anticline.

The Coconino Sandstone is mainly large-scale crossbedded fine-grained sandstone and subordinately flat-bedded sandstone, particularly near the top of the formation. It is about 650 feet thick in the Black Box of the San Rafael River and appears to be about 880 feet thick in the Blackwood and Nichols 1–28 test, sec. 28, T. 24 S., R. 10 E. (American Stratigraphic Co. log 705). It is overlain unconformably (McKee, 1938, p. 29–31) by the Kaibab Limestone (Gilluly and Reeside, 1928, p. 63–64), which consists mainly of limestone, but contains thin shaly and sandstone beds near its base. The Kaibab ranges from 0 to about 85 feet in thickness in the swell.

The correlations of the Coconino Sandstone and Kaibab Limestone of the San Rafael Swell with the type sections of these formations in the Grand Canyon area have long been regarded as tenuous. Gilluly and Reeside (1928, p. 64) pointed out that the sandstone-limestone sequence was similar not only to the Coconino and Kaibab in the southern Colorado Plateau but also to the Weber and Park City succession of north-central Utah. McKee (1954) pointed out that the Kaibab of the San Rafael Swell is younger faunally than the type Kaibab and that the type Coconino thins progressively northward, probably pinches out, and is not north of the Utah-Arizona border.

Earlier McKee (1938, p. 213–214) showed that the Kaibab of the San Rafael Swell rested unconformably on the Cedar Mesa(?) Sandstone Member of the Cutler Formation. Stratigraphic relations in the large number of oil tests recently drilled in the Green River desert east of the swell indicate that the Coconino of Utah is at least partly correlative with the White Rim Sandstone Member of the Cutler Formation. The Kaibab of Utah is probably in part correlative with the Park City Formation (F. G. Poole, oral commun., 1964).

TRIASSIC SYSTEM

MOENKOPI FORMATION

The Moenkopi Formation of Early and Middle(?) Triassic Age underlies most of the Sinbad Country. It is covered by the Chinle Formation on isolated mesas and is eroded away in the deeper canyons. The Moenkopi is generally absent in the east-central part of the swell where Permian or older rocks are exposed.

The Moenkopi Formation ranges in thickness from about 465 feet to more than 800 feet. It thickens to the northeast, west, and southwest from a minimum thickness near Straight Wash (fig. 3). The Moenkopi is divided into a lower unit, the medial Sinbad Limestone Member, and an upper unit. Where it is exposed below the Chinle or in the deep canyons, the Moenkopi has a steep slope with a prominent cliff formed by the Sinbad Member. Much of the upland in the west-central part of the swell is a surface of low relief supported by the Sinbad Member.

The lower unit ranges in thickness from about 65 feet in Straight Wash to about 185 feet in the northern part of the swell. From base upward it consists of chert-pebble conglomerate or slabby-bedded sandstone, interbedded fissile siltstone, and massive fine-grained sandstone beds; just below the Sinbad, thin-bedded limestone or dolomite is interlayered with siltstone. Except in the northern part of the swell, the siltstone is greenish gray and pyritic, and it weathers to a yellow tan which pervades the whole unit. The massive sandstone beds are brown as a result of petroleum staining, but they weather white.

The medial Sinbad Limestone Member is about 35 feet thick near Straight Wash and 46 feet thick near Temple Mountain; according to J. H. Stewart and C. H. Scott (written commun., 1953), it is 86 feet thick in the Muddy Creek at the south "dip out" of the Kaibab Limestone and 61 feet thick about 1 mile southeast of Block Mountain in the west-central part of the swell. The Sinbad is mainly composed of limestone or dolomite, but it also contains thin interbedded siltstone and sandstone layers. The carbonates composing most of the unit range areally from mostly dolomite to mostly limestone. The member is mainly dolomite near Temple Mountain and near Tomsich Butte,

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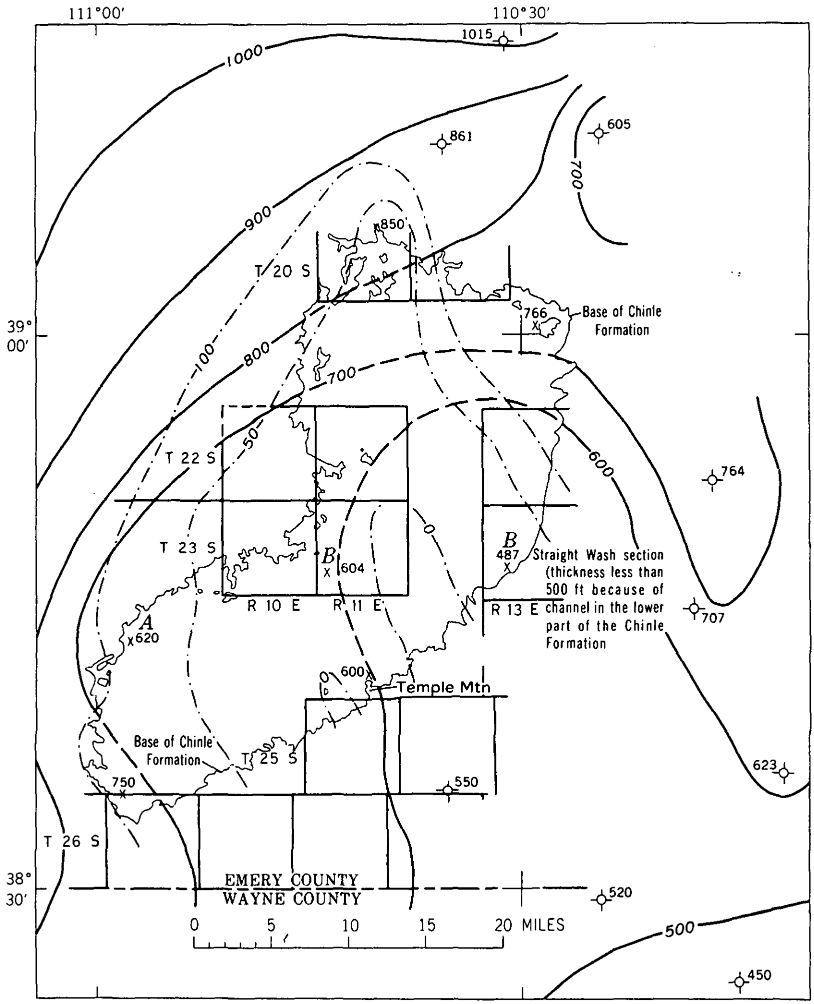

EXPLANATION

——700—— — —
Approximate isopach of Moenkopi Formation
Dashed where partly eroded. Contour interval 100 feet

—·—·—50—·—·—
Isopach of interval between siltstone marker bed and top of Moenkopi Formation
Locally eroded. Contour interval 50 feet

x 766
Measured thickness, in feet, of Moenkopi Formation

861
Drill hole showing approximate thickness, in feet, of Moenkopi Formation

FIGURE 3.—Isopach map of the Moenkopi Formation, San Rafael Swell. *A*, Thickness measured by Keys and White (1956). *B*, Thickness measured by Stewart, Williams, Albee, and Raup (1959).

mainly limestone in the northern part of the swell, and both limestone and dolomite in the central part of the swell near Tan Seep. The dolomite typically weathers tan; the limestone, gray. Analyses, by C. G. Angelo, Wayne Mountjoy, and R. G. Havens, of composite grab samples of tan and gray carbonate-rich rocks collected about 1 mile east of Tan Seep show variation in composition as follows:

Laboratory No.	Description	Analyses (percent)						
		Radiometric	Chemical		Semiquantitative spectrographic			
		eU	$CaCO_3$	$MgCO_3$	Si	Al	Fe	Mn
SRR-17A (254-546).	Gray limestone (Sinbad).	<0.001	91.96	<1.00	3.0	1.5	0.7	0.15
SRR-17B (254-547).	Yellowish-tan dolomitic limestone (Sinbad).	<.001	59.4	32.2	1.5	.7	1.5	.15

The upper and thickest unit of the Moenkopi Formation is composed of alternating strata of siltstone, silty sandstone, and fine-grained sandstone in that order of abundance. The siltstone is fissile and mainly reddish brown, although it is pale green in a belt which extends northwest across the swell (fig. 9), and it is mottled red, purple, and pale green locally near the top of the formation. The pale-green and mottled siltstones are probably altered, and they are discussed more fully under "Altered rocks." The silty sandstone, also reddish, occurs throughout the unit in ledge-forming beds which average 3 feet in thickness. The fine-grained sandstone, commonly in only the lower half of the upper unit, is in beds which average about 20 feet in thickness; it weathers almost white, is commonly petroliferous, and is typically crossbedded on a very fine scale. The basal contacts of the individual fine-grained sandstone units are disconformable; the sandstone fills minor scours cut into the silty sandstone and siltstone strata which, in contrast, are everywhere in apparently conformable succession. In the southwestern part of the San Rafael Swell, the uppermost Moenkopi is gypsiferous.

The Moenkopi Formation rests disconformably on the Kaibab Limestone and is overlain, with probable slight angular unconformity, by the Chinle Formation. The angularity is shown by small variations in the thickness of the Moenkopi over wide areas, specifically in a zone between nearly continuous silty sandstone beds and the upper contact of the formation (fig. 3). The silty sandstone marker beds occur throughout the swell except on the east flank north of Temple Mountain where they have been eroded. The interval thickens to the north and south to about 100 feet. The absence of the uppermost Moenkopi in a northwesterly belt, together with the pattern of thinning of all the Moenkopi (fig. 3), indicates that the formation was gently arched along a northwesterly trend and partly eroded before the deposition of the Chinle Formation.

CHINLE FORMATION

The Chinle Formation of Late Triassic age crops out in a belt around the swell and as remnants on isolated buttes and mesas in the Sinbad Country (fig. 2). It is represented in the swell by four units, named in ascending order: the Temple Mountain, Monitor Butte, Moss Back, and Church Rock Members. The Moss Back Member is composed predominantly of light-colored sandstone and conglomerate and was deposited in a broad river system. The Monitor Butte, Temple Mountain, and Church Rock Members, in contrast, are mainly composed of varicolored claystone, siltstone, and fine-grained sandstone which were probably deposited in lakes, flood plains, and smaller river systems. The formation appears to become richer in sandstone to the north and northwest, as reflected particularly by the character of the Church Rock Member and also by an increase in thickness of the Moss Back Member to the northwest.

Channel-fill sandstones and conglomerates of the Temple Mountain, Monitor Butte, and Moss Back Members are the host rocks of most of the uranium deposits of the San Rafael Swell.

The thickness of the Chinle Formation ranges from about 215 feet, 1⅔ miles north of Tomsich Butte, to at least 370 feet locally. It averages about 300 feet near the Delta mine in the southern part of the swell, 360 feet near Temple Mountain in the southeastern part, and 350 feet on Mexican Mountain in the northeast corner. According to J. H. Stewart, C. H. Scott, and A. C. Gorveatt (written commun., 1953), the Chinle is 361 feet thick at Straight Wash, 349 feet thick in Buckhorn Wash, 368 feet thick at Horseshoe Bend (NE. cor. sec. 24, T. 22 S., R. 10 E.), and about 264 feet thick near the Lucky Strike mine.

MONITOR BUTTE AND TEMPLE MOUNTAIN MEMBERS

DEFINITION AND CORRELATION

The lowermost part of the Chinle Formation is composed of the Monitor Butte and Temple Mountain Members. These rocks were apparently included in the Shinarump Conglomerate, now considered a member of the Chinle, by Gilluly (1929, p. 88), Baker (1946), and Hunt, Averitt, and Miller (1953, p. 48–52), and in the Moenkopi Formation by W. L. Stokes (written commun., 1946). Recent detailed studies have shown that both the Monitor Butte and Temple Mountain are more like the Chinle Formation than the Moenkopi in color, grain size, sorting, clay mineralogy, and carbonaceous materials; hence, their assignment to the Chinle Formation.

The Monitor Butte and Temple Mountain Members are lithologically distinctive, but both are thin and intergrade locally; in this report they are generally considered together as composing the basal unit of the Chinle Formation. The Monitor Butte Member is characterized by less massive siltstone strata and by well-sorted fine-grained feldspathic sandstone, locally in contorted beds; the Temple Mountain Member, by massive mottled siltstone beds and lenses of medium- to coarse-grained quartzose sandstone. The Monitor Butte Member correlates with rocks exposed in the lower part of the Chinle Formation in the Orange Cliffs, White Canyon, and Monument Valley areas, Utah (Stewart, 1957). The Temple Mountain Member is formally recognized only in the San Rafael Swell, but it resembles rocks found in the lower part of the Chinle Formation in the Circle Cliffs, White Canyon, and other areas in Utah. Rocks of both the Monitor Butte and Temple Mountain locally show purple and white mottling and contain chert and carbonates of epigenetic origin. These rocks are altered equivalents of originally red rocks and are considered more fully in the section on "Altered rocks."

THICKNESS

The undivided Monitor Butte and Temple Mountain Members range from 0 to about 100 feet in thickness in the swell (pl. 1). They are thinnest in a northwest-trending belt inferred to have crossed the central part of the San Rafael Swell. They are also thin or locally absent in other areas because of channeling by streams that deposited the Moss Back Member.

Channels of the Moss Back, Monitor Butte, and Temple Mountain Members are shown by local variations in thickness (pl. 1). The lower part of the Chinle is unusually thin where the Moss Back has filled channels in the basal Chinle; it is unusually thick where the Monitor Butte or Temple Mountain Members have filled channels in the Moenkopi. Channel directions were inferred from the thickness relations and, locally, from studies of sedimentary structures. The directions and extent of the channels are uncertain because of the general thinness of the Chinle outcrop belt and the relatively thick cover and rough terrain outside the outcrop belt which have largely precluded tracing channels by drilling.

STRATIGRAPHY

The basal part of the Chinle Formation in the southern San Rafael Swell is composed mainly of strata assigned to the Monitor Butte Member; the basal part in the northern part of the swell is composed mainly of the Temple Mountain Member. In the intervening country lithologies typical of both members can be recognized. In general, the lowermost part of the Chinle Formation—the undivided Monitor Butte and Temple Mountain Members—is mainly siltstone but it also contains claystone, sandstone, and conglomerate. The siltstone and claystone are varicolored: red is the dominant color, but reddish purple, purple, and pale green are common. The silty or clayey rocks are slope forming and generally poorly fissile and weather to a frothy surface indicating swelling clays. The Monitor Butte Member is characterized by thin interbeds of reddish-purple to pale-green or gray ripple-marked fine-grained sandstone, by beds as much as 40 feet thick of tan to gray thin-bedded well-sorted fine-grained feldspathic sandstone, and by steeply dipping apparently slumped interbeds of fine-grained sandstone and mudstone. The Temple Mountain Member is characterized by beds of massive mottled siltstone with local beds and pipes of medium- to coarse-grained poorly sorted quartzose sandstone. The variation of the lower part of the Chinle Formation in the San Rafael Swell is shown in the following stratigraphic sections. In keeping with the general northerly change in the character of the basal unit of the Chinle Formation, the southernmost section is entirely Monitor Butte Member, the northernmost entirely Temple Mountain Member, and the other two include strata of both members.

Section of the lower part of the Chinle Formation measured 1,500 feet N. 12° E. of the Delta mine

	Feet
Moss Back Member, Chinle Formation (not measured).	
Sandstone, conglomeratic, very calcareous, silty, gray-green, finely laminated.	
Monitor Butte Member, Chinle Formation:	
Siltstone, reddish-brown; grades upward to reddish purple; thin pale-green zone below Moss Back; abundant nodular calcareous masses; slope forming, frothy weathering	9.0
Siltstone, purple and gray; grades upward to purple; calcareous nodule zone at base of unit; slope forming, frothy weathering	12.0
Siltstone, red; grades upward to purple and brownish red (limonitic); slope forming, frothy weathering	11.5
Siltstone, varicolored purple, brownish-red (limonitic), pale-green; upper part is slickensided on small scale; slope forming, frothy weathering; bedding not generally apparent in upper 4 units of Monitor Butte Member	5.5
Siltstone and sandstone; red with minor gray streaks parallel to bedding; thin bedded, ripple marked; forms a minor cliff	22.4
Sandstone, white, fine-grained, lenticular; thickens to the southwest; unit is equivalent to the Hunt sandstone of economic usage (see Delta mine area)	.6
Total of Monitor Butte Member	61.0
Moenkopi Formation (not measured):	
Siltstone, mottled purple, red-brown; pale green in pattern controlled by fissility and fractures, grades downward into red-brown siltstone.	

Section of the lower part of the Chinle Formation measured on the east side of Cistern (Bell) Canyon about 1,000 feet north of the "dip out" of the unit.

	Feet
Moss Back Member, Chinle Formation:	
Sandstone, locally conglomeratic, petroliferous, cliff-forming (not measured).	
Sandstone, conglomeratic, highly calcareous	1.0
Lower part of Chinle Formation, mostly Monitor Butte Member:	
Sandstone, pale-green, finely laminated; thin interbeds of gray siltstone and limestone-pebble conglomerate, forms steep slope	9.5
Limestone-pebble conglomerate, gray, massive	4.0
Mudstone, purple; thin bleached green zone below pebble conglomerate, blocky weathering, montmorillonitic(?)	7.5
Siltstone, mottled purple, green, and red, resistant, massive; veinlets and irregular masses of red chert at top of unit (possibly correlates with Temple Mountain Member)	4.0
Total of lower part of Chinle Formation	25.0
Moenkopi Formation (not measured):	
Siltstone, reddish-brown.	

Section of the lower part of the Chinle Formation measured on the northeast corner of Temple Mountain

[Generalized description of a section measured by J. H. Stewart and C. H. Scott, 1953]

	Feet
Moss Back Member, Chinle Formation, total thickness	93.9
Monitor Butte and Temple Mountain Members, Chinle Formation:	
Siltstone, greenish-gray, medium-light-gray and minor dark-yellowish-orange, clayey, firmly cemented, noncalcareous, structureless; nonsplitting but fractures into irregular granule-size fragments; unit is poorly exposed, lower contact gradational	8.9
Siltstone; grayish-purple, light-greenish-gray, and minor pale-red-purple, intermixed irregularly, well cemented, noncalcareous; fractures like uppermost unit	17.6
Sandstone, pale-red-purple, grayish-red, pale-red, and light-greenish-gray, very fine grained to fine-grained, fair sorting, firmly cemented, noncalcareous; lenticular unit of thin horizontal laminae, very thin to thin sets of small- to medium-scale cross-laminae; papery to flaggy splitting, forms minor vertical cliff; grades into enclosing units	3.6
Sandstone, clayey, white-grayish-pink and light-brown, coarse- to very coarse grained, poorly sorted; composed of angular to subround quartz and 5 percent orange and gray minerals; interstices filled with white clay comprising about 20 percent of rock	4.0
Total of Monitor Butte and Temple Mountain Members	34.1
Moenkopi Formation (not measured):	
Siltstone and sandy sandstone.	

Section of the lower part of the Chinle Formation measured at the Uneva prospect

[Measured by J. G. Moore and C. C. Hawley, 1956]

	Feet
Moss Back Member, Chinle Formation (not measured).	
Temple Mountain Member, Chinle Formation:	
Claystone, varicolored yellow, pale-green, and purple; color changes parallel to bedding; fissile, grades downward into reddish-purple massive siltstone and sandstone; white medium- to coarse-grained sandstone pipes in siltstone and sandstone; pipes perpendicular to the bedding, terminated upward by thin sandstone beds	22.0
Sandstone, greenish-gray with irregular purple areas, fine-grained; grades into unit above, and columnar structures (pipes) extend down into this unit; thin sandstone bed forms base of unit	20.0
Siltstone, gray, fissile, jarosite-stained; contains abundant carbonaceous material; grades laterally into sandstone	4.0
Sandstone, gray, poorly sorted; coarse-grained with scattered quartz pebbles and conglomerate seams; contains thin partings and sheared mudstone pebbles; carbonaceous; contains sparse copper minerals; unit is ore bearing laterally	5.0
Siltstone and claystone, red, finely laminated, in part shaly; has thin sandstone interbeds	3.0
Siltstone and sandstone, red; scattered coarse quartz grains; massive outcrop; upper contact gradational	6.5
Sandstone, white to tan, fine-grained, calcareous, thin-bedded	3.0
Total of Temple Mountain Member	63.5
Moenkopi Formation (not measured):	
Siltstone, red-brown; no apparent disconformity at top.	

Sandstone in the lower part of the Chinle Formation forms thick lenses which fill intraformational scours or scours cut into the upper part of the Moenkopi. These lenses, which are lenticular and which represent remnants of ancient river-channel fills, contain most of the uranium found in the Monitor Butte and Temple Mountain Members in the San Rafael Swell. In the southern part of the swell, locally mineralized sandstone lenses of the lower part of the Chinle are at or near the Delta mine, the Spanish Trail prospect, the Lucky 7 prospect, on Green Vein Mesa, and in the Cistern Canyon Annex–Lower Wild Horse Point areas (pl. 1); similar lenses are in the northern part of the swell on Mexican Mountain and in several other places.

Interlayered sandstone and mudstone with slumped bedding is exposed in the lower part of the Chinle near thick sandstone lenses exposed at the Delta mine and Lucky 7 prospect. The occurrence of slumped rocks at these two places suggests that such rocks may be more abundant near channel-fill sandstones, and so the presence of slumped beds may indicate nearness to a channel.

The direction of streamflow, as indicated by orientation of channel-fill sandstones and sedimentary trends, was variable during the deposition of the Monitor Butte and Temple Mountain Members. The Monitor Butte channels exposed along the southeast flank of the swell, at least locally, trend northwest (pl. 1; Hinckley and others, 1955); the major basal channel of the lower part of the Chinle near the Delta mine trends west-southwest. The major channel on Green Vein Mesa trends about north (as indicated by minor scours outlined by detailed structure contours, R. D. Miller and K. J. Rogers, written commun., 1953). The large Temple Mountain Member channels of the northwestern part of the swell trend mainly northwest.

Where lenticular sandstone is present at the base of the Chinle, the Chinle-Moenkopi contact is easily recognized; where the sandstone is absent, the contact is indicated by the lesser fissility, scattered quartz grains, frothy weathering, and carbonaceous material of the Chinle; and where Chinle-Moenkopi siltstones are juxtaposed, the exact contact may be difficult or impossible to draw. In the northeastern part of the swell, both the upper and lower contacts of the lower part of the Chinle Formation (Temple Mountain Member) are difficult to define. The mottled siltstone and quartzose sandstone typical of the lower part of the Chinle are separated from undoubted Moenkopi by thin zones of red siltstone and local feldspathic sandstone of questionable affinity. Similar red siltstone also locally overlies mottled siltstone and sandstone.

The contact of the Monitor Butte and Temple Mountain Members is probably gradational, and although lithologic differences exist between the basal part of the Chinle Formation of the northern part of the swell and that of the southern part, the two members that compose the basal part of the Chinle are believed to be only slightly different in age. South of South Temple Wash, resistant mottled siltstones typical of the Temple Mountain Member are scattered stratigraphically in rocks that are otherwise more like the Monitor Butte Member, and suggest interfingering of the two members. At Straight Wash, sandstone typical of the Temple Mountain is overlain with apparent conformity by sandstone typical of the Monitor Butte, and both sandstones are in the same channel structure. In the Delta mine area, where a disconformity can be postulated between the mottled rocks and the Monitor Butte sandstones, the lowermost mottled rocks are altered Moenkopi and no Temple Mountain Member is present. Finally, the silicic rock characteristic of mottled rocks and previously interpreted (Robeck, 1956, p. 2501, 2506) as a syngenetic accumulation at an unconformity is shown to be epigenetic by local low-angle fracture control, and by the fact that it locally crosses into the overlying Moss Back Member.

Robeck (1956) called this rock silica or jasper; as it is of secondary origin, it is here called jasperoid.

Difficulty in separating the two lowermost members of the Chinle seems to be a problem shared with the other members, as Stewart (1957, p. 447) has noted similar difficulties in separating some upper units of the Chinle, such as the Church Rock and Owl Rock Members.

MOSS BACK MEMBER

The Moss Back Member of the Chinle Formation, composed mainly of sandstone or conglomerate more resistant to erosion than the overlying and underlying strata, forms a bench or ridge, depending on its dip, that encircles the swell inside the San Rafael Reef. The Moss Back is also exposed on isolated buttes or mesas, such as Flat Top, in the Sinbad Country. The member was deposited in a broad northwest-trending belt under alluvial-plain conditions; the average direction of transport, indicated by crossbedding, is about N. 60° W. (Stewart and others, 1959, p. 512–515, fig. 77).

The Moss Back is the host rock of the large uranium deposits of the Temple Mountain district, as well as of smaller deposits including those of the Cistern, Lucky Strike, and Dirty Devil mines.

CORRELATION AND THICKNESS

Sandstone and conglomerate which crop out above the Monitor Butte and Temple Mountain Members in the swell were formerly included in the Shinarump Conglomerate. Stewart (1957) showed, however, that the rocks generally mapped as Shinarump in southeast Utah contain three main units that can be distinguished by areal distribution and lithology; these units were named the Shinarump, Monitor Butte, and Moss Back Members. Stratigraphic studies and mapping show that the sandstone-rich medial Chinle of the swell correlates with the Moss Back Member, whose type section is in the eastern part of White Canyon area, San Juan County, Utah.

Thickness of the Moss Back Member (fig. 4) ranges from about 12 feet, 1,500 feet N. 12° E. of the Delta mine, to nearly 170 feet in the west-central part of the swell. It averages about 60 feet near the Delta mine and 90 feet near Temple Mountain. In the swell the Moss Back can be divided areally into southwestern, northeastern, and central parts (fig. 4). In the southwestern part the Moss Back is generally less than 80 feet thick, but its thickness changes abruptly because of channel deposits at the base of the unit, where it may exceed 80 feet (pl. 1). In the northeastern part, the Moss Back is less than 80 feet thick and is nearly blanketlike. In the broad central area (fig. 4), which probably represents the main system of the Moss Back river-channel deposits, the member is generally more than 80 feet thick and thickens gradually to the northwest.

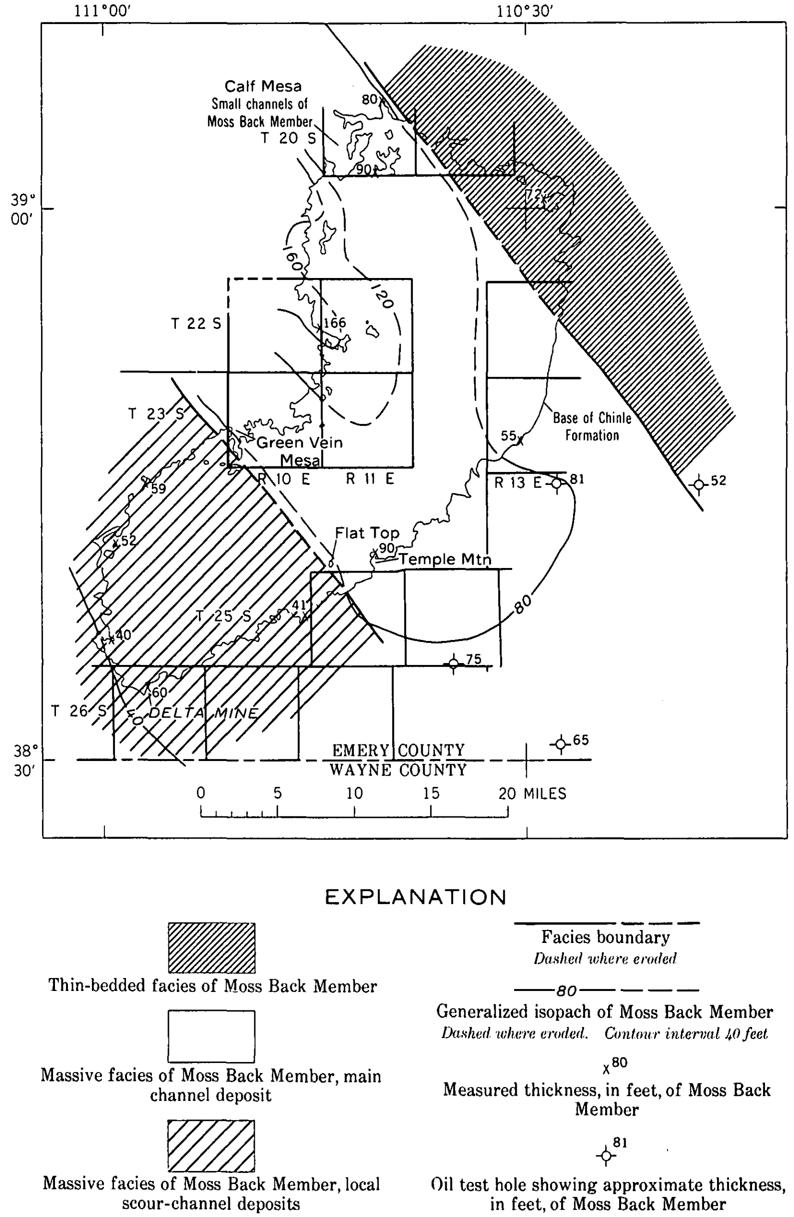

FIGURE 4.—Generalized isopach map of the Moss Back Member of the Chinle Formation, San Rafael Swell.

STRATIGRAPHY

In the San Rafael Swell the Moss Back Member is composed of two main facies: a massive facies, which is dominant, and a thin-bedded facies, which occurs locally.

The massive facies is composed of several distinct rock types in a more or less constant sequence that was first recognized on the southeast flank of the swell by W. L. Stokes (written commun., 1946). In stratigraphic order the predominant components are: (1) quartzose-pebble conglomerate, (2) fine- to medium-grained massive sandstone, (3) limestone-pebble conglomerate, and (4) fine-grained platy-weathering sandstone. These units interfinger and intergrade, and one or more may be locally absent, so there are exceptions to the typical stratigraphic sequence.

The thin-bedded facies of the Moss Back, which occupies the northeastern area shown in figure 4, lies near the northern pinchout of the Moss Back and probably correlates with similar rocks that were described by Stewart, Williams, Albee, and Raup (1959) near the northern limit of Moss Back deposition in the canyon of the Colorado River. Where exposed in the northeastern swell area, the thin-bedded facies is composed mainly of interbedded calcareous-pebble conglomerate, fine-grained sandstone, and siltstone. Siltstone interbeds are partly red in contrast to their pale-green color in most of the Moss Back. Similar rocks are also exposed between Tomsich Butte and the Conrad mine on the west flank of the swell (too local to be shown in fig. 4). The thin-bedded facies grades into the massive facies near Buckhorn Wash on the north flank of the swell and near the San Rafael River gap on the east flank.

Quartzose-pebble conglomerate and subordinate amounts of sparsely conglomeratic sandstone and conglomeratic mudstone compose the basal part of the Moss Back Member. In many places the conglomeratic mudstones are the rocks immediately above the basal contact of the Moss Back Member and are distinguished from mudstones of the lower part of the Chinle by their quartz-pebble content. The conglomeratic sandstones are tan, coarse bedded, and well cemented with calcite (also the main cement in the conglomerates). Coalified or silicified wood is moderately abundant, but petroleum is rarely near the base of the Moss Back Member. The pebbles of the conglomerate and conglomeratic sandstone are rounded, as much as 2 inches in diameter, and are, in order of abundance, chert, quartzite, quartz, limestone, calcareous siltstone, and silicified fossiliferous limestone.

Fine- to medium-grained massive sandstone generally overlies the basal quartzose conglomerate of the Moss Back Member, and as seen from a distance it forms a white band on the Moss Back cliff. The sandstone is well sorted, is cross stratified, and on a fresh surface is tan to almost black because of petroleum staining. It is slightly to moderately calcareous but is less calcareous than typical underlying or overlying units. Light-colored mudstone layers and lenses are interspersed with the dominant sandstone of the unit.

Limestone-pebble conglomerate, which typically overlies the massive sandstone, contains abundant flat to rounded limestone and calcareous siltstone pebbles and sparse siliceous pebbles. The rocks are well cemented with carbonate and on weathering form a distinctive brown cliff. Coalified or silicified wood is more abundant here than in the massive sandstone but less abundant than in the quartzose conglomerate and conglomeratic sandstone.

Fine-grained platy-weathering crossbedded sandstone, which contains scattered quartzose pebbles, forms the uppermost part of the Moss Back Member at most places. It is more thinly bedded and contains more siltstone than the lower rocks. The sandstone is mainly light colored, and at Temple Mountain it contains limonite or pyrite concretions. Because of its thin bedding and high silt content, the sandstone appears to be gradational with the overlying Church Rock Member.

The contact of the Moss Back and Church Rock is generally sharp and can be distinguished by finer grain size, red colors, and sparsity of quartzose pebbles in the basal Church Rock. Color alone is not a certain guide because color contacts cut locally across bedding. In a few places, as in the first large canyon north-northwest of Tomsich Butte, the contact appears gradational over as much as 40 feet, and in The Chimney (a canyon) the Moss Back and Church Rock intertongue (pl. 4).

CHANNELS IN THE CHINLE FORMATION

Ancient channel structures of several sizes and types are found in the Chinle Formation in the San Rafael Swell. The largest channel structure, which shows the main trend of the deposits of the Moss Back Member river system, is marked by thick Moss Back which extends northwestward across the central part of the swell (fig. 4). The strip of thick Moss Back lies approximately in the middle of the northwest-trending belt of Moss Back deposition on the Colorado Plateau (Stewart and others, 1959, fig. 77) and is partly coextensive with thin combined Monitor Butte and Temple Mountain Members (pl. 1) and with thin Moenkopi Formation (fig. 3). The channel also coincides approximately with the axis of a northwest-trending anticline which predates the northeast-trending San Rafael anticline. The northeast edge of this major channel is marked by relatively thin silty thin-bedded Moss Back Member, which is interpreted as a flood-plain deposit. The south edge of the major channel is approximately at the southern 80-foot isopach shown in figure 4.

Smaller channel structures can generally be classed into three groups, here called scour, lens, and intraformational. Each of these types can be most easily visualized in cross section, approximately as they are seen in the steep slopes and cliffs formed by the formation (fig. 5). Scour channels are typically found at the base of the Moss Back Member; they are elongate, are cut into the underlying strata (generally the Monitor Butte or Temple Mountain Members), and are filled with sandstone and conglomerate of the Moss Back. The floors of large scour channels are irregular, and smaller scale spoon-shaped scours occur at the base of major scour channels. The small-scale scours are the main ore-bearing structures in the Moss Back Member in the southwestern part of the swell. Lens channels are typical of the claystone- and siltstone-rich Monitor Butte Member; they are elongate sandstone-rich units enclosed or nearly enclosed by claystone or siltstone. As defined here, intraformational channels are thickened, elongate lenticular sandstone or conglomerate-rich bodies in a sandstone- or conglomerate-rich unit such as the Moss Back Member.

The largest scour channel of the San Rafael Swell is the Tomsich Butte channel of the Moss Back Member, named for its good exposures on and near the butte on the west flank of the swell. Its course (pl. 1) is largely inferred because of erosion and the thin Chinle outcrop belt. The channel, as exposed near Tomsich Butte, is about a mile wide, and it fills a gentle trough cut into the Monitor Butte Member. It is considered to be bounded approximately by the 40-foot isopachs of the lower part of the Chinle. Within the channel structure where the stream cut more deeply, smaller isolated scours occur; at Tomsich Butte they are outlined by 0-foot isopachs of the lower part of the Chinle. These scours or lows in the base of the main channel deposit are the obvious "channels" noted by prospectors.

The Tomsich Butte channel (pl. 1) can be projected from the southeast flank of the swell near the Cistern mine, westward to the Chinle outcrop on the west flank, thence northward through Tomsich Butte,

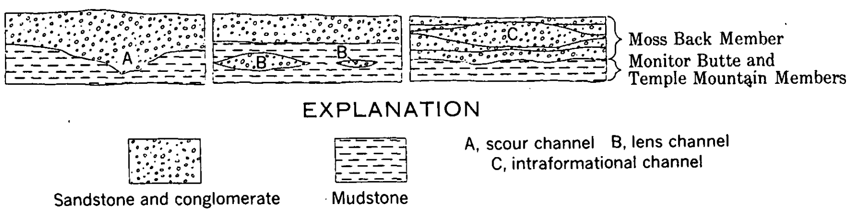

FIGURE 5.—Diagrammatic classification of channel structures of the Chinle Formation.

then northwestward to north of the butte, and northeastward through the Conrad and Lucky Strike mine areas. The projection westward from the Cistern mine is speculative, but the pattern of the 20-foot isopach of the lower part of the Chinle and mainly west-dipping Moss Back crossbeds of the area are consistent with this interpretation. The axis of the channel can be followed closely for short distances north and south of Tomsich Butte. On Tomsich Butte the trend of the channel is nearly north to south, as shown by the direction of the 40-foot isopachs of the lower part of the Chinle, by the average current direction of N. 6° E. indicated by crossbedding (A. C. Gorveatt, written commun., 1953; F. G. Poole, written commun., 1958), and by north-trending ore-bearing scours at the base of the channel exposed in the Dirty Devil group of mines. North of the butte, the channel swings northwestward, as shown by the 40-foot isopach of the lower part of the Chinle and by the northwesterly scours exposed at the base of the channel in the Green Dragon claims (pl. 1). From here north to near the Conrad mine, the postulated channel is deeply buried, and the exposed Moss Back belongs to a thin, thin-bedded facies. The thin-bedded Moss Back, whose average thickness is about 40 feet, begins on the northeast flank of the channel about 1 mile north-northeast of Tomsich Butte and continues to the northeast for about 8,000 feet to a point in the vicinity of the Joshua claims. Near this point, the Moss Back changes back to the massive facies, in which local deep northeast-trending ore-bearing scours occur at the Conrad (G. W. Chase, oral commun., 1958) and Lucky Strike mines.

A smaller Moss Back scour channel crops out on the southwest flank of the swell west-northwest of the Delta mine where a northwest-trending zone of relatively thick Moss Back Member (pl. 1) contains an ore-bearing scour at the Little Susan mine. An apparently isolated Moss Back scour channel is exposed in Chute Canyon at the Little Erma mine, and small scour channels are found at the base of the member at several other places, including Calf Mesa in the northern part of the swell. The intraformational type of channel, which has previously been described (Hawley and others, 1965), contains most of the ore in the Temple Mountain district.

CHURCH ROCK MEMBER

The red siltstone, red to gray sandstone, and limestone-pebble conglomerate exposed between the top of the Moss Back Member and the Wingate Sandstone have been correlated with the Church Rock Member of the Chinle Formation (Stewart, 1957, p. 459–460). The Church Rock Member is exposed under the San Rafael Reef around the entire swell, but it is only a remnant on a few of the larger inlying buttes, such as Window Blind Butte in the northern part of the swell.

The Church Rock Member is thinnest in the southwestern part of the swell and thickest in the eastern part. On the southwest flank, it is only 130 feet thick near the Conrad mine, 147 feet thick 1 mile northwest of the Little Susan mine, 160 feet thick at the Delta mine, and 167 feet thick at the Lucky Strike mine. On the east flank, as measured by J. H. Stewart, C. H. Scott, and A. C. Gorveatt (written commun., 1953) and by us, it is 252 feet thick at Straight Wash, about 240 feet thick near Temple Mountain, and 225 feet thick on Mexican Mountain. It is 195 feet thick at Buckhorn Wash and 178 feet thick at Horseshoe Bend (NW. cor. sec. 24, T. 22 S., R. 10 E.).

The Church Rock Member is composed mainly of red siltstone, red thin-bedded silty sandstone, gray limestone-pebble conglomerate, light-colored calcareous sandstone, and subordinately of red, purple, and pale-green claystone. Silty rocks are very characteristic of the Church Rock in the southern part of the swell, but sandstone and conglomerate beds interlayered with siltstone characterize a sandy facies north of a point just south of Temple Mountain on the east side of the swell and near Tomsich Butte on the west side. The sandstone layers are as much as 20 feet thick at Temple Mountain and 65 feet thick in the northern part of the swell. One unit which is a marker bed and appears generally continuous north of Temple Mountain has locally been called the Black ledge (Stewart, 1957).

The thick sandstone beds in the Church Rock in the northern part of the San Rafael Swell are locally weakly radioactive; west of Calf Mesa they show radioactivity of about twice background; and at Temple Mountain they are locally mineralized.

The contact of the Church Rock Member and the overlying Wingate Sandstone is sharp and apparently conformable.

TRIASSIC AND JURASSIC GLEN CANYON GROUP

The Glen Canyon Group consists of the Wingate Sandstone of Late Triassic age, the Kayenta Formation of Late Triassic(?) age, and the Navajo Sandstone of Triassic(?) and Jurassic age. The rocks of the group are relatively resistant to erosion and form the massive barrier—the Reef—that surrounds the San Rafael Swell. The total thickness of the group at Temple Mountain is about 1,200 feet; at Straight Wash it is about 1,066 feet (J. H. Stewart and A. C. Gorveatt, written commun., 1953).

The Wingate Sandstone, the only unit of the group that we studied in some detail, is predominantly pale-orange to tan fine-grained sandstone in large-scale planar crossbeds; rarely it contains thin beds of limestone (or dolomite), and at Temple Mountain it is petroliferous with the upper part having thin mudstone splits, some of which are mudcracked. The fine-grained sandstone within a few feet of the base of the formation contains scattered frosted coarse sand.

The thickness of the Wingate averages slightly more than 300 feet; it is about 360 feet at Temple Mountain, 281–349 feet near the Delta mine (averaging 320 ft), 314–378 feet near Tomsich Butte (averaging 336 ft), and 305 feet at Straight Wash. The Wingate is overlain disconformably by the Kayenta Formation.

The Kayenta Formation is composed dominantly of sandstone with lesser amounts of siltstone and limestone-siltstone-pebble conglomerate. The sandstone is typically crossbedded on a small scale, and beds are thinner than in either the underlying Wingate Sandstone or overlying Navajo Sandstone. The Kayenta averages about 200 feet in thickness.

The Navajo Sandstone is composed of both massive and crossbedded fine-grained sandstone; the lower part of the formation has local minor mudstone splits and thin beds of limestone (or dolomite); it is typically more massive than the upper part, which is crossbedded in large-scale simple sets. The Navajo Sandstone is about 600 feet thick.

The rocks of the Glen Canyon Group are locally mineralized, and they have been extensively altered (p. 57). The Wingate Sandstone contains small ore bodies at Temple Mountain, and the Navajo Sandstone contains weakly uraniferous copper ore at the Copper Globe mine on the west flank of the San Rafael Swell.

POST-GLEN CANYON ROCKS

The Navajo Sandstone of the Glen Canyon Group is overlain, in stratigraphic order, by the Carmel Formation, Entrada Sandstone, Curtis Formation, and Summerville Formation which together compose the San Rafael Group of Middle and Late Jurassic age. Rocks of the group include a large proportion of marine strata in contrast to the continental strata of the Chinle Formation and Glen Canyon Group. The Summerville is overlain by the continental Upper Jurassic Morrison Formation which contains fairly important uranium deposits in the Green River district and small deposits at other places on the periphery of the swell.

IGNEOUS ROCKS

Several thin discontinuous northwest-striking dikes of analcite-biotite diabase are exposed on the southwest side of the swell (fig. 2, pl. 2). More numerous dikes are exposed west of the mapped area in a rather well defined north-trending swarm that extends about 10 miles north and 10 miles south from Heep Mountain (Gilluly, 1929, pl. 30; fig. 2 this report). Composite sills occur in the Carmel Formation, in

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the Entrada Sandstone, and rarely in the Morrison Formation along the trend of the dike swarm.

The dikes within the area studied are nearly vertical and are less than 5 feet thick; some are in several segments (pl. 2) as a result of displacement along cross fractures or of en echelon filling of nearly parallel fractures. The dikes are alkalic mafic igneous rock that is greenish black and porphyritic. The phenocrysts, as much as 3 mm across, are chiefly altered olivine and pyroxene and, as reported by Gilluly (1929), some are biotite. The fine-grained groundmass contains plagioclase, pyroxene, magnetite, some biotite, and, as reported by Gilluly (1929), analcite and thompsonite. Locally the rocks are altered and contain calcite and kaolinite. The dikes contain radioactive elements, for laboratory determinations of radioactivity show as much as 0.006 percent eU (Keys, 1954). The dikes are probably Tertiary, although stratigraphic evidence permits dating only as post-Morrison. The average (geometric mean) chemical composition of the dikes, in percent, as calculated from four semiquantitative analyses, follows.

Major constituents		Trace elements			
Si	M	Ba	0.15	Nb	0.002
Al	M	Be	Tr.	Ni	.015
Ca	M	Ce	.05	Pb	.005
Mg	M	Co	.005	Sr	.2
Fe	7	Cr	.03	V	.05
K	6	Cu	.01	Y	.04
Na	6	Ga	.003	Zr	.03
		La	.015		

NOTE.—M, >10 percent.

WARM SPRINGS

Warm springs issue from near the Kaibab-Moenkopi contact in a zone that extends for about one-half mile along the San Rafael River in the northern part of the swell (fig. 2). The springs have been briefly described by Hess (1913b) and W. S. Keys (written commun., 1955).

The springs bubble hydrogen sulfide and probably carbon dioxide and have formed local sulfur and travertine deposits. According to Keys, temperatures range from 60° to 73°F. Slight anomalous radioactivity is found at several of the springs—the maximum radioactivity recorded was twice background. Copper sulfate is being formed at one spring, and Keys reported cobalt- and iron-bearing sulfate coatings on twigs.

STRUCTURE

The rocks of the San Rafael Swell have been folded into a broad northeast-trending anticline which resembles other large upwarps of the Colorado Plateau in its asymmetry and doubly plunging form. Locally the rocks have been faulted, cross folded, and involved in pipe-like collapse structures. Most of the rocks are jointed, and bedding-plane and associated low-angle fractures are found near some lithologic discontinuities. The structure of the San Rafael Swell is shown on plate 2, and the folds and collapse structures are shown at a larger scale in figure 6.

FOLDS

The San Rafael anticline is a markedly asymmetric doubly plunging anticline about 100 miles long and 40 miles wide; only its central part is shown on plate 2. Rocks on the west side of the anticlinal crest dip gently westward; those on the east side dip gently eastward near the crest of the fold, but about 6–9 miles southeast of the crest they steepen abruptly to form a monocline. The entire San Rafael structure can be described as a monocline with anticline and syncline (Kelley, 1955, fig. 8).

Along the southeast flank of the swell the rocks dip as much as 20° SE. on the monoclinal flexure. Northward from Ernie Canyon, which is about 7 miles northeast of Temple Mountain, and especially northward from Straight Wash, the monocline steepens abruptly to a point 2½ miles north of Straight Wash, where the Chinle Formation is overturned and dips about 85° W. (pl. 2). The steepening is particularly pronounced north of a high-angle east-striking fault which swings northeastward into the bedding as it enters the nearly vertical Moenkopi Formation.

The crest of the anticline is crenulated owing to cross warps that are apparently confined to structurally higher parts of the anticline and to the sinuosity of the crestline itself (pl. 2, fig. 6). In the south-central part of the swell, the anticline trends about N. 30° E.; to the north the crestline generally trends N. 65° E. through the Tan Seep area but is locally sinuous and has a pronounced bend or warp near secs. 35 and 36, T. 36 S., R. 10 E. North from about sec. 13, T. 23 S., R. 11 E., the crestline swings more northward.

The crestline is divided into two major anticlinal folds in the northern part of the swell and into three in the southern part. In both areas the major amount of uplift occurs on the more westerly crestlines (pl. 2, fig. 6, this report; Gilluly, 1929, pl. 30).

The cross warps occur principally in two groups—one in the west-central part of the swell and one in the southeastern part. Each group lies opposite a major bend in the crestline of the swell. In the west-central group, the Family Butte syncline (pl. 2, fig. 6) can be traced for about 6 miles; it projects toward a synclinal warp mapped west-

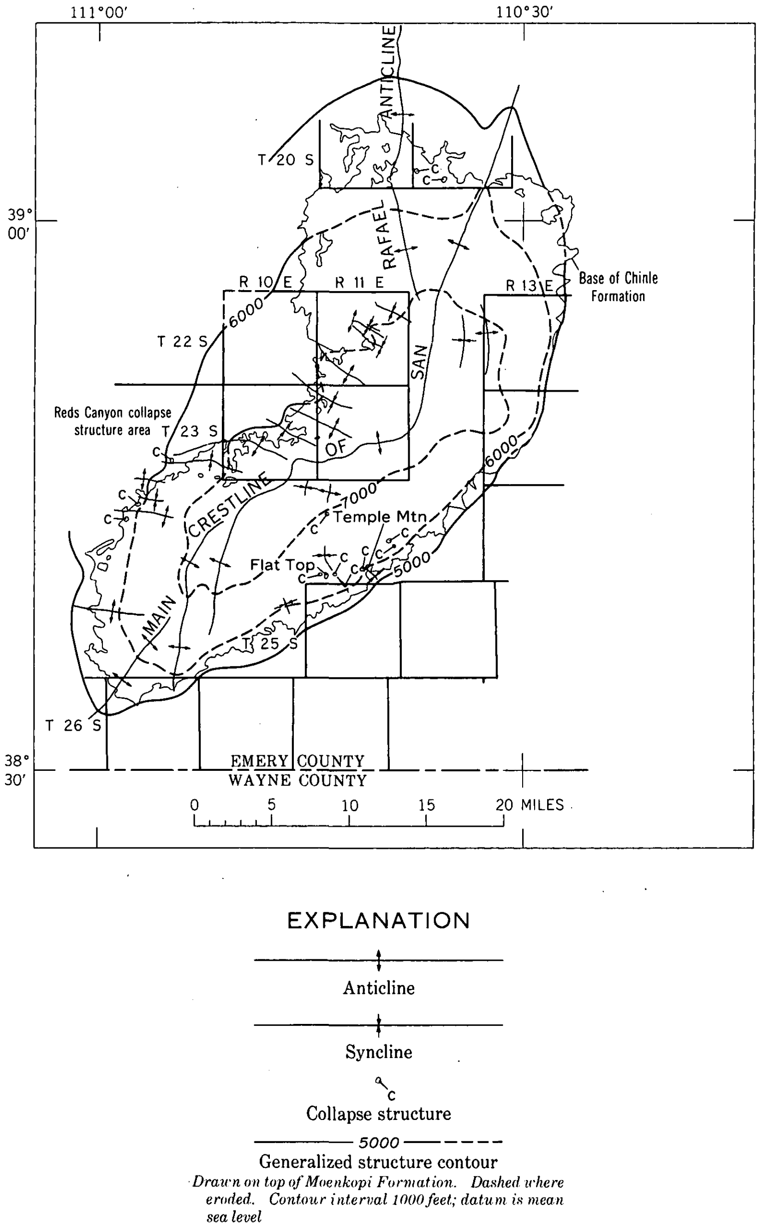


FIGURE 6.—Folds and collapse structures of the San Rafael Swell.

ward another 10 miles by Gilluly (1929). On the southeast side of the swell near Temple Mountain, cross folds can be traced for as much as 3 miles.

COLLAPSE STRUCTURES

The collapse structures of the San Rafael Swell, hereafter generally called collapses, are downward-displaced pluglike masses of altered rock as much as 3,000 feet across. The strata involved range from Late Triassic to Permian in age; the collapsed rocks themselves have been either downfaulted or downwarped into stratigraphically lower rocks. Collapses occur near Temple Mountain on the southeast flank of the swell, in Reds Canyon and Sulphur Canyon on the west flank, and east of Window Blind Butte in the northern part of the swell. These areas lie within the areas of cross warping or subsidiary folding. The collapses in the Temple Mountain and Reds Canyon areas show a close spatial relation to cross warps; those near Window Blind Butte are in the downwarped area between main splits of the San Rafael crestline (fig. 6).

Six of the collapses are somewhat uraniferous, but only the Temple Mountain collapse contains appreciable quantities of uranium.

TEMPLE MOUNTAIN AREA

Eight collapse structures are exposed within a radius of 4 miles of Temple Mountain. Five, including the Temple Mountain collapse structure, are described in some detail by Hawley, Wyant, and Brooks (1965); these collapses and others near Temple Mountain have also been described by Keys and White (1956) and by Kerr, Bodine, Kelley, and Keys (1957).

The Temple Mountain collapse is a composite structure probably composed of three rather distinct collapse elements. Each collapse element is a downfaulted mass; all are in a larger saucer-shaped structural depression about 3,000 feet long, which, in turn, is in the east-trending central part of a generally northwest-trending synclinal cross fold. Most of the rocks in the collapse are brecciated, but in general they were downfaulted as coherent and identifiable stratigraphic units. Thus it can be determined that the brecciated rocks in the collapse were derived from the Moenkopi Formation, Chinle Formation, and Wingate Sandstone. According to drilling information (Keys and White, 1956), the Kaibab Limestone and the Sinbad Limestone Member of the Moenkopi are missing in the collapse, and the collapse bottoms on the Coconino Sandstone; that is, the Coconino has not been displaced nor extensively fractured.

Rocks in and near the collapse have been altered, principally by bleaching, formation or modification of clay minerals, and redistribution of carbonates. Calcite and dolomite were generally removed within the collapse; and dolomite, siderite, and calcite were deposited in concentrations in the adjacent sedimentary rocks. Some uraniferous asphaltite and metallic minerals also formed within the collapse structure during the alteration period.

The other collapses in the Temple Mountain area are similar but smaller, and in general they have a higher proportion of downwarped to downfaulted rocks than does the Temple Mountain collapse. Two small collapses east of Flat Top are mainly in the axis of a synclinal cross fold, and the Flat Top collapse itself is on the flank of this same structural feature (pl. 2, fig. 6). Three of these smaller collapses—the Flat Top collapse, the collapse due west of Temple Mountain, and the collapse about 7,500 feet southwest of Flat Top—contain some uraniferous rock.

REDS CANYON AND VICINITY

Three collapse structures—the South Reds Canyon, North Reds Canyon, and Little Joe collapses (pl. 2)—are exposed on the west side of the San Rafael Swell north of Tomsich Butte. The South Reds Canyon collapse (collapse 8, Keys and White, 1956), drilled by the U.S. Atomic Energy Commission, and the Little Joe collapse have been described by Kerr, Bodine, Kelley, and Keys (1957).

The South Reds Canyon collapse is a composite structure which on the surface consists of two pluglike collapses about 500 feet apart. As exposed, the larger plug is a knob-shaped mass of altered brecciated sandstone that stands well above the general surface of the Moenkopi Formation (fig. 7). Like the Temple Mountain collapse, the South Reds Canyon collapse includes material from several formations, but in contrast to the Temple Mountain collapse, it bottoms in or possibly below the Coconino (fig. 7). U.S. Atomic Energy Commission diamond drill hole V–12 was drilled to a depth of 791 feet in the southern element of the composite collapse and penetrated strongly fractured rocks ranging in age at least from that of the Wingate Sandstone and possibly that of the Kayenta Formation of Late Triassic(?) age to that of the Coconino. The drill hole penetrated probable Coconino Sandstone at an altitude of about 4,812 feet, which is 380 feet below the expected position of the Coconino, based on the thickness of the Moenkopi Formation and other intervening strata. The basal Chinle contact was intersected at about 5,073 feet, a fact indicating a subsidence for that unit, relative to the projected contact, of about 770 feet.

No uranium minerals are known from the collapse but the rocks at the surface are locally copper stained.

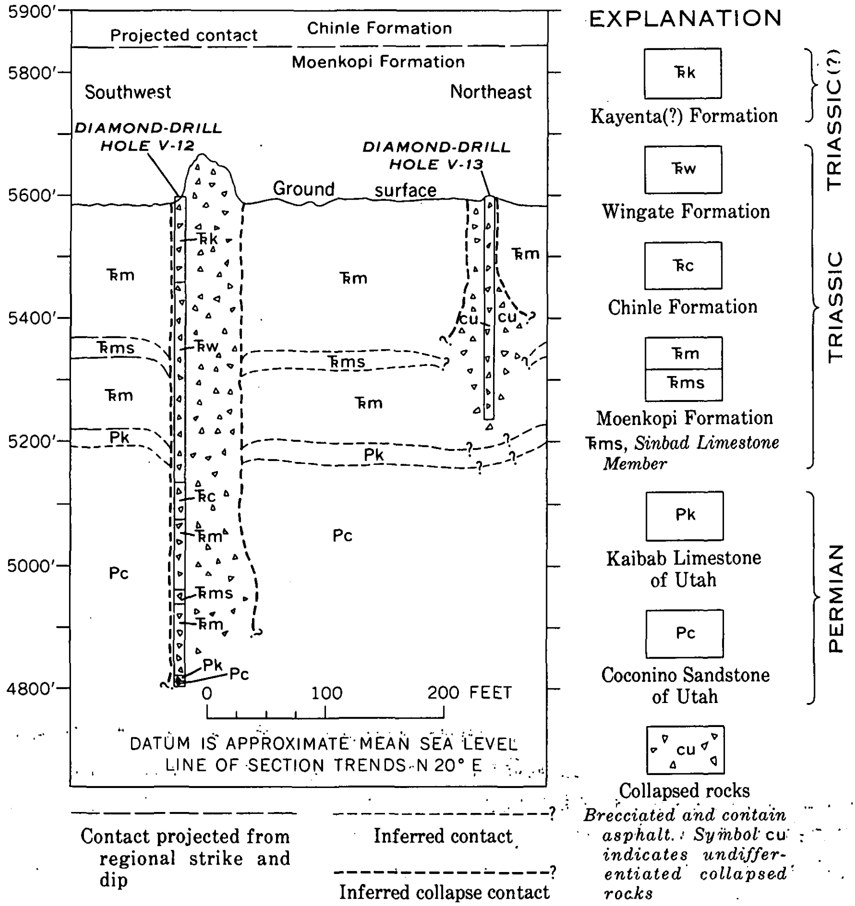


FIGURE 7.—Geologic section through South Reds Canyon collapse structure. From Keys and White (1956).

The North Reds Canyon collapse is about a mile northeast of the South Reds Canyon collapse. As exposed, the collapse is a roughly circular block, about 150 feet across, of sandstone of the Moss Back Member and mudstone of the Monitor Butte Member surrounded by siltstone of the Moenkopi Formation. At first glance the collapse appears to be a large landslide block of sandstone of the Moss Back Member, but on close inspection the block shows a dish-shaped structure with the amount of dip decreasing inward; the rocks on the west edge of the collapsed block now dip vertically. The outermost part of the "dish" is anomalously radioactive and contains chalcocite(?) and secondary copper minerals.

The Little Joe collapse is in Sulphur Canyon about 3½ miles northeast of the North Reds Canyon collapse (pl. 4). It is a roughly circular brecciated mass less than 100 feet across which is near the Family Butte fault zone and also near the axis of the Family Butte syncline (pl. 2). The surrounding surface rocks are sandstone and siltstone of the Church Rock Member of the Chinle Formation, and the rocks in the collapse were derived from the Church Rock and overlying Wingate Sandstone. The upper part of the exposed collapse is an altered, locally brecciated pluglike mass of Wingate Sandstone. Uraniferous asphaltite (as well as nonradioactive asphalt and dead oil) is found in the brecciated rocks at the Little Joe collapse. The asphaltite and sparse secondary copper-uranium minerals are confined to the peripheral parts of the collapsed rocks and occur in disseminated nodules, thin veins, and nodules in blocks of brecciated Wingate.

NORTH PART OF THE SWELL

Collapses in the northern part of the swell have not been studied in detail; they appear, however, to be similar to those near Temple Mountain and Reds Canyon. Two of the collapses are east of Window Blind Butte on the northeast flank of a large structural depression (pl. 2); the third collapse is about 3 miles east of Window Blind Butte. These collapses are not radioactive.

ORIGIN

The collapse structures probably formed as the result of collapse or sagging of rocks into voids created by the solution of stratigraphically lower rocks at sites partly determined by small folds. As proposed by D. G. Wyant (written commun., 1953), Keys and White (1956), and Kerr, Bodine, Kelley, and Keys (1957), the voids were created in part by solution of carbonate rocks. However, at least in the Temple Mountain collapse, the thickness of the carbonate sequence above the bottom of the collapse is not adequate to account for the amount of subsidence (Keys and White, 1956) unless it is assumed that the collapse flares outward at depth or that siliceous rocks have also been dissolved locally. The extensive subsidence observed in the South Reds Canyon collapse can probably be accounted for by solution of part of the upper Paleozoic carbonate-bearing sequence that lies below the Coconino.

BEDDING-PLANE FRACTURES

Bedding-plane and related low-angle fractures are at or near some formational or lithologic contacts, particularly near the contact of the Moenkopi and Chinle Formations. Displacement on these fractures is presumably small. The bedding-plane fractures formed near the Moenkopi-Chinle contact in places where there is a noticeable lithologic change, as from siltstone to claystone or from sandstone to siltstone.

For example, where the basal part of the Chinle is claystone and the underlying Moenkopi is siltstone, fractures formed chiefly at the Chinle-Moenkopi contact. Where the lower part of either Monitor Butte or Temple Mountain Member is a massive siltstone, fractures formed in the thin mudstone zone between the massive siltstone of the lower part of the Chinle and the basal part of the Moss Back Member. The fractures are mostly in the mudstone, but in places they are in sandstone, where they form microbrecciated rock (fig. 15). The fractures discussed here are distinct from the small slickensided fractures of diverse trend that are characteristic of the montmorillonitic layers of the lower part of the Chinle.

The bedding-plane fractures typically overlie low-angle fractures that die out downward. Low-angle fractures, with the effects of regional dip removed, associated with bedding-plane fractures in the lower part of the Chinle in the Temple Mountain district are plotted in figure 8. The poles of the fractures have a strong steep maximum dip of about S. 65° E., a condition showing that a set of fractures strikes about N. 25° E. and dips southeast at a low angle. The strike of this set of fractures is slightly north of the local strike of rocks near Temple Mountain but is close to the general trend of the San Rafael anticline.

Bedding-plane fractures undoubtedly are common on the Colorado Plateau, but they have apparently been dismissed as unimportant by most geologists and have not been mentioned. A few geologists, however, recognized their possible importance as controls of mineralization or alteration. Finnell (1957) noted the relation of mineralization to fracturing at the contact of the Shinarump and Moenkopi at the Monument 2 mine in northern Arizona, and many years ago Hess (1913a, p. 162–163) proposed that bedding-plane fracturing in the Morrison Formation, due to uplift of the San Rafael Swell, was a control of uranium deposition in the Green River desert area. Butler, Loughlin, and Heikes (1920, p. 153, 588) noted apparent localization of the silver-uranium deposits of the Silver Reef district of southwest Utah in part by bedding-plane fracturing, reflected primarily in the shearing of thin shale units. In the San Rafael Swell, the bedding-plane fractures localized mineralization or alteration; these are discussed in subsequent parts of the report.

HIGH-ANGLE FAULTS

Major faults or fault sets in the swell can be grouped generally into (1) east-striking faults in the southern part of the swell, (2) northwest-striking faults near Tomsich Butte, (3) the Family Butte fault, (4) north-northeast-striking faults on the west side of the swell, and

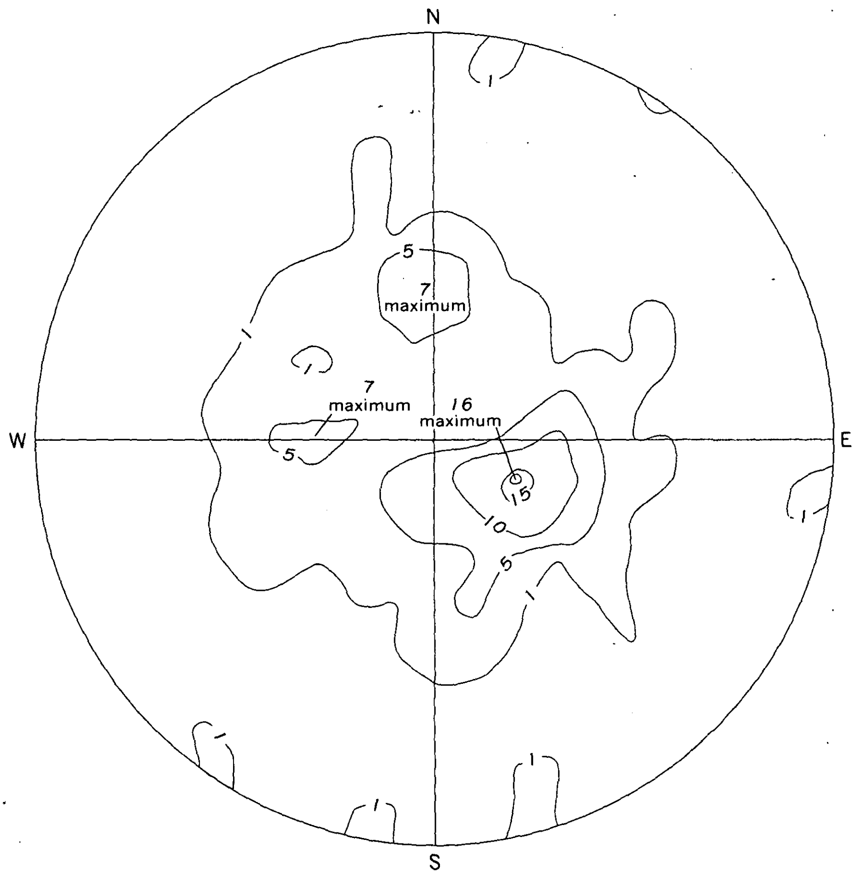


FIGURE 8.—Schmidt net diagram of poles of 102 fractures in the lower part of the Chinle Formation, Temple Mountain area, plotted on upper hemisphere. Numbers indicate percentage of poles.

(5) northwest-striking faults north of Temple Mountain and Family Butte. Most of the faults have maximum vertical displacements of less than 200 feet and, with the probable exception of some north-northeast-striking faults, have normal displacements; all but a very few dip 60° or more.

The larger faults near Temple Mountain (Hawley and others, 1965) strike east, east-northeast, and west-northwest and form an en echelon horst and graben pattern. The amount of vertical displacement, which is as much as about 250 feet, changes abruptly along the strike of the individual faults, and the displacement is taken up by other faults in the en echelon pattern. Faults in this group near Temple Mountain extend westward from near the Reef across the main anticlinal axis almost to the large northwest-striking faults near Tomsich Butte.

The southwestern part of the swell, from 2 miles east of the Delta mine northward almost to Tomsich Butte and south to where Muddy Creek leaves the Reef, has no large faults, but it is bounded on the north and northeast by a curving fault that is one of the two large northwest-striking faults exposed near Tomsich Butte.

Northward from the Tomsich Butte graben (pl. 2), minor faults are exposed near the Lucky Strike mine, but the next major fault is the Family Butte fault which can be traced from Cat Canyon east to the crest of the swell. This fault has a maximum vertical displacement of almost 250 feet; it trends slightly north of west and is subparallel to the Family Butte syncline.

North of Family Butte on the west side of the swell and north of Temple Mountain on the east, the major faults belong to two sets which strike north-northeast and northwest. Most of the north-northeast-striking faults, such as the Cat Canyon fault, are west of the main swell axis; they are of particular interest because they parallel the axis and locally are high-angle reverse faults. The largest of the northwest-striking faults on the west side of the swell, such as the Road Hollow fault, are virtually axial-plane faults in synclinal cross folds. On the east side a large northwest-striking fault that cuts the San Rafael Reef near Straight Wash projects toward a major northwest-trending fault on the Green River Desert which was mapped by Baker (1946, pl. 1, north half); this fault is one of the very few exposed faults in the swell that extend beyond the swell.

Although most faults are fairly well exposed, the relations between different sets could not be determined during reconnaissance mapping of structure. Possibly the north-northeast-striking faults are somewhat earlier than northwest-striking faults, because they appear to be displaced by northwest-striking faults east of Tomsich Butte and on Swazy Flat (pl. 2).

AGE AND ORIGIN OF STRUCTURES

The rocks exposed in the San Rafael Swell range in age from Pennsylvanian and Early Permian to Late Cretaceous. Below the Pennsylvanian are other sedimentary rocks which lie on the Precambrian basement. All these rocks are involved in the San Rafael anticline, and on this basis alone the anticline is considered to be post-Cretaceous in age.

Studies of the Permian and Triassic sedimentary rocks show, however, that the present anticline is superimposed on an older northwest-trending fold that formed after the deposition of the Hermosa (?) Formation and was intermittently active at least to the hiatus between the Moenkopi and Chinle Formations. The presence of this old fold has been demonstrated both structurally and stratigraphically. By graphically removing the structural effect of the Monument upwarp on the rocks southeast of the swell, McKeown and Orkild (1958) found a northwest-trending anticline extending from a point south of the Colorado River to the San Rafael Swell in the Hermosa and Rico Formations. The continuation of this fold into the San Rafael Swell is apparently marked by the northwest-trending belt of thin Moenkopi and by the slight angular unconformity at the top of the Moenkopi (fig. 3).

Although of little importance to the present structure, the old northwest-trending fold apparently controlled the regional alteration of the Moenkopi Formation, influenced the thickness of the Moenkopi Formation, and combined the Monitor Butte and Temple Mountain Members of the Chinle Formation. The thick Moss Back Member of the swell also partly coincides with the crest of the old fold.

This northwest-trending fold is probably related to northwest-trending structural features of the salt anticline region of the Paradox basin. As shown on large-scale structure maps of the Colorado Plateau (Kelley, 1955, figs, 2, 5, 6), a northwest structural trend is locally conspicuous on the Colorado Plateau, particularly in the Uncompahgre–salt anticline region, and it extends to the San Rafael Swell. The folding of the salt anticlines took place sporadically from Paradox time onward. These northwest-trending structural features date back to movement of the Uncompahgre structural element in Pennsylvanian and Permian time, but some were rejuvenated during the Tertiary.

The present San Rafael anticline was most probably formed in early Tertiary time. Spieker (1946, p. 155–156; 1954, p. 11–13) showed that monoclinal folding similar to that on the east flank of the swell took place in pre-Flagstaff, post–North Horn time (Paleocene) in the Sixmile Canyon area of central Utah, and he believed that other monoclinal folds on the western part of the Plateau probably formed between the middle and later part of the Paleocene. Hunt (1956, p. 57, 73–77) proposed that the folding and uplift of the San Rafael Swell took place in the Paleocene to Miocene, with folding in the Paleocene, some differential upwarp during late Eocene to Oligocene, and epeirogenic uplift in the Miocene.

Hypothetically the general structure of the swell can be explained by more than one mechanism, including vertical tectonics and lateral compression (Baker, 1935, p. 1501). The detailed aspects of the structure—such as the arcuate monocline, north-northeast-striking reverse faults, local overturning, and crenulated crestal region—are believed more consistent with at least local compressional stress than with simple vertical uplift. The arcuate pattern of the monocline together with local overturning suggests that the east flank of the swell could overlie a reverse fault of arcuate form or a reverse fault bounded on the north and south by east-striking tear faults. A reverse fault on the Farnam dome, a subsidiary dome on the northwestern part of the San Rafael anticline, has been proved by drilling (Peterson, 1954; Mahoney and Kunkel, 1963).

The apparent confinement of crossfolds to the San Rafael anticline, and the association of collapse structures with subsidiary folds strongly indicate that these structures are nearly contemporaneous with the main folding. A possible mechanism for the formation of the cross folds is suggested by their relation to major bends of the crestline: secondary compressive forces set up by warping of the main crest could have caused the cross folds.

The bedding-plane faults found near the Moenkopi-Chinle contact could logically have also been formed during major folding because of the couple set up by slippage of structurally higher beds toward the anticlinal crest. The southeast dip direction and northeast-trending strike of the associated low-angle fractures of the Temple Mountain district are consistent with this idea.

Most high-angle normal faults of the swell are probably somewhat younger than the major folding, cross warps, collapse structures, and bedding-plane slips, although the fact that they are nearly confined to the San Rafael anticline indicates that they are related to that structural feature. Most normal faults show crosscutting relations to cross folds of the Temple Mountain district (Hawley and others, 1965) and in addition are dated as relatively late by the fact that they dominantly postdate the ore. The cross warps, bedding-plane slips, and collapse structures dominantly predate the ore. A few faults, such as the northwest-trending fault zone that is exposed about a mile southeast of Straight Wash (pl. 2), may reflect the older northwesterly structural trend, but the present surface expression of this trend is post-upwarp because the fault zone is not deflected by the monocline.

ALTERED ROCKS

Altered rocks are widely distributed in the San Rafael Swell, and two types of alteration of regional extent can be distinguished. In one type large volumes of rock are altered, including rocks of the Moenkopi Formation, the combined Monitor Butte and Temple Mountain Members, and the Glen Canyon Group. In the second type, relatively small volumes of rock are altered locally, but alteration is also on a regional scale. The main example of this type of alteration is the thin bleached zone which underlies the Moss Back Member and other sandstone-rich units of the Chinle Formation and, less commonly, other formations.

ALTERED ROCKS IN THE MOENKOPI FORMATION

The Moenkopi Formation has been altered in a northwest-trending belt which crosses the swell and continues to the southeast under the Green River Desert to the Green River (fig. 9; McKeown and Orkild, 1958, fig. 5).

The alteration of the Moenkopi consisted of bleaching of originally red rocks, formation of pyrite, and introduction of petroleum. The fresh altered rocks are pale green; the weathered altered rocks are pale yellowish brown, locally limonitic, and commonly gypsiferous. The fresh bleached siltstone contains pyrite in nodules and in small (as much as 2 mm across) disseminated cubes, and pyritohedra and locally petroleum or asphalt.

The altered Moenkopi, as drawn in figure 9, represents a belt where the entire thickness of the Moenkopi is altered; actually, alteration is much more extensive than this because the alteration boundary flares downward, and the lower part of the Moenkopi is altered in most of the swell. A cross section of the altered zone would approximate a section drawn through an inverted bowl; in detail the cross section would be irregular because bleaching extends out as tongues along sandstone-rich beds of the Moenkopi.

The belt of complete bleaching is nearly coextensive with the old northwest-trending anticlinal structure and coincides partly with relatively thin Moenkopi (fig. 3) and thin combined Monitor Butte and Temple Mountain Members (pl. 1).

The bleached and pyritized rocks of the Moenkopi Formation are shown to be altered equivalents of red rock because contacts between pale-green and red rocks locally cut crossbedding planes (see also Baker, 1946, p. 55) and because, except for color and pyrite, the lithology of the red and green rocks is the same. Marker beds such as sandstone can be traced across the color boundary. The relation of the belt of altered rocks to the old northwest-trending anticlinal structure also suggests that they were formerly red rocks that have been altered.

The alteration was most likely caused by the migration of petroleum and associated natural gas and water into the old northwest anticline, as suggested by its distribution and by the presence of petroleum residues in the altered rocks (Johnson, 1957, p. 45). If the alteration had been due to petroleum and connate fluids, further alteration could have resulted from later migration caused by changed structural or hydrologic conditions. Late alteration is shown, at least on a small

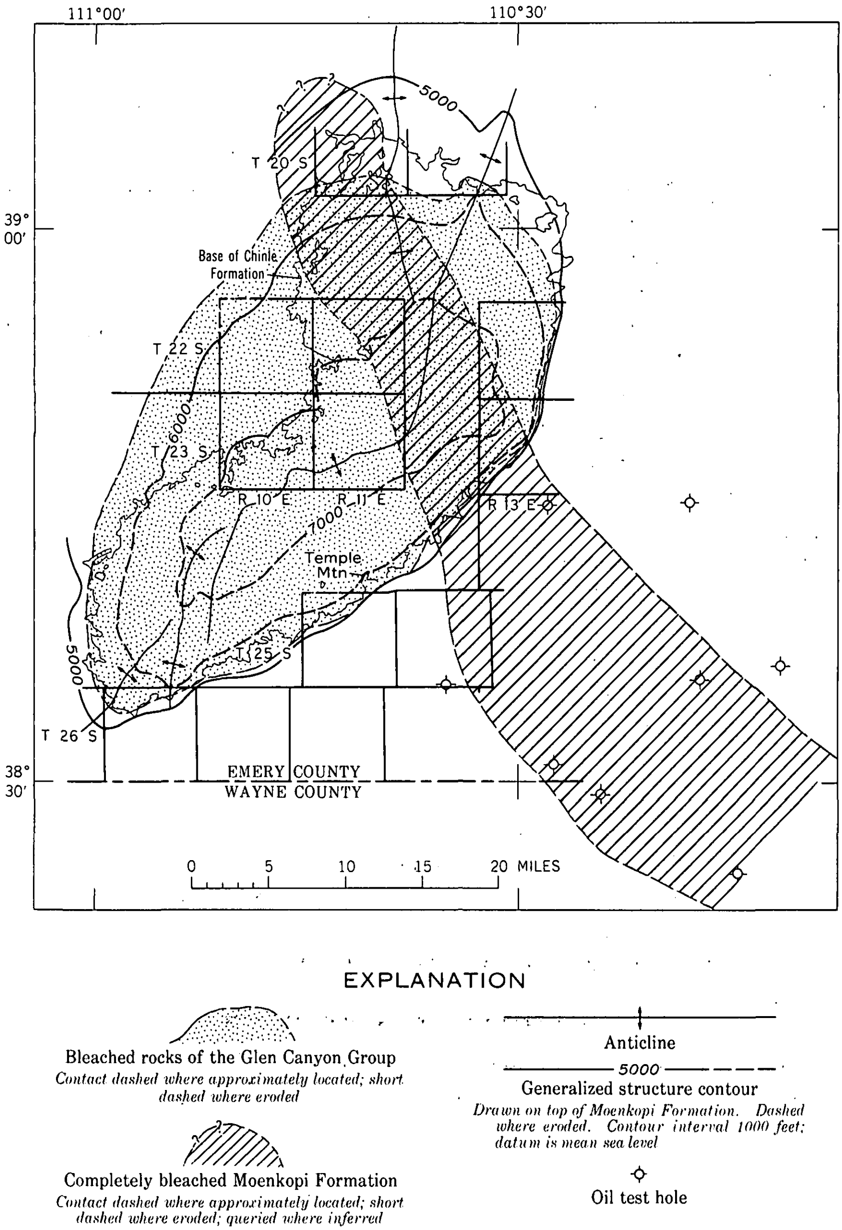


FIGURE 9.—Altered rocks in the Moenkopi Formation and Glen Canyon Group, San Rafael Swell.

scale, by the altered rocks and asphalt on fault zones that displace the main Moenkopi alteration contacts.

ALTERED ROCKS IN THE LOWER PART OF THE CHINLE FORMATION

Mottled red, white, and purple rocks are widely distributed in nearly stratigraphic zones in the Monitor Butte and Temple Mountain Members of the Chinle Formation and in the uppermost part of the Moenkopi Formation in the San Rafael Swell. Similar rocks are also found elsewhere on the Colorado Plateau near the base of the Chinle Formation. Judging by their mode of occurrence, chemistry, and mineralogy, the white and purple rocks are mainly altered equivalents of red rocks. The distinctive color patterns and other unusual features of these rocks have been noticed by other geologists, but unfortunately have been described in only a few places. Finch (1953a, b) recognized the altered rocks when he proposed that there was a belt of altered rocks in the upper part of the Moenkopi and lower part of the Chinle in southeast Utah. He called this belt the "purple-white band" after the distinctive "purple" and "white" mottling of the rocks. Recently Schultz (1963) described the mottled rocks and their mineralogy, and Abdel-Gawad and Kerr (1963), Johnson (1957, 1964), and Kerr and Abdel-Gawad (1964) discussed the genesis of the altered zone.

A brief summary of Hawley's views on the alteration was published in 1958; at that time he proposed that alteration was epigenetic and partly controlled by low-angle fractures. Hematite, kaolinite, barite, and carbonates were listed as alteration products. Previously, McKeown and Hawley (1955, 1956) had shown the existence of anomalously high trace quantities of several metallic minerals in the purple-white rocks.

DESCRIPTION AND OCCURRENCE

The altered rocks characteristic of the combined Monitor Butte and Temple Mountain Members typically consist of mottled claystone, siltstone, sandstone, and conglomerate. Although the mottling is the most obvious result of alteration, formation of jasperoid, carbonates, barite, kaolinite, sulfides, and uraniferous substances also resulted.

Small-scale mottling of red, purple, and green color is characteristic of at least part of the altered rocks at most places and is especially conspicuous in the more massive siltstones of the lower part of the Chinle Formation. Typically, in the rocks that are mottled on a small scale, dark-reddish-brown areas (10*R* 3/4) are surrounded by a thin "white" zone (pale green, 5*G* 7/2) that is in a grayish-purple (5*P* 4/2) matrix. The red areas become larger downward, and commonly a transition zone of red rock veined with pale green and purple rocks lies between the mottled and the completely red rocks. The mottling may not have obvious controls (fig. 10*A*), or it may be controlled by fractures (fig. 10*B*) or by bedding or pipelike structures of the lower part of the Chinle. The massive siltstone beds typical of the Temple Mountain Member in many places are purple and white with only small remnants of red.

The mottled rocks generally grade upward into a thin zone of completely bleached pale-green rock which apparently is the zone of most intense alteration and which generally coincides with a zone of bedding-plane shearing. This zone contains most of the concentrations of jasperiod, kaolinite, and metallic minerals or mineraloids but only a small amount of hematite and carbonates. The upper contact of this bleached zone is locally sharp; but where the overlying rock is soft nonfissile mudstone, the upper contact is also gradational into apparently unaltered red rock through a zone of purplish-red or carbonatized rock.

Purple-white rocks are most striking in the combined Monitor Butte and Temple Mountain Members where the rocks are rich in claystone and mudstone. They are not found in those areas where the Moenkopi is completely bleached and where pervasive bleaching extended up into the lower part of the Chinle. Locally, the fine-grained sandstones of the Monitor Butte Member and the coarse-grained quartzose sandstone of the Temple Mountain Member are also mottled purple and white.

Purple-white rocks may be at any stratigraphic position in the lower part of the Chinle Formation. Near the Delta mine (see p. 46 for detailed description) two zones of purple-white rocks are present—

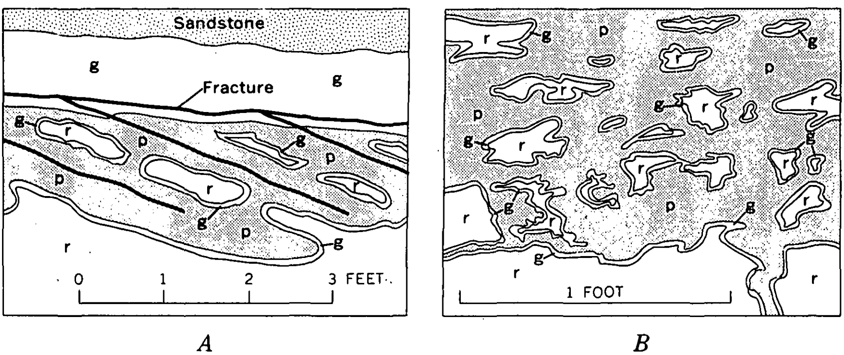


FIGURE 10.—Purple-white mottling in Temple Mountain and Monitor Butte Members, Chinle Formation. *A*, Typical mottling in massive siltstone, Temple Mountain Member. *B*, Fracture-controlled mottling in siltstone below massive sandstone, Monitor Butte Member; r, dark reddish brown; p, grayish purple; g, pale green.

one at the Chinle-Moenkopi contact and the other about in the middle part of the Monitor Butte Member. Near Tomsich Butte purple rocks are in the lower part of the unit, and the most intensely altered rocks are near the Moenkopi-Chinle contact. At Temple Mountain purple-white altered rocks are found throughout the lower part of the Chinle. They are also widely distributed stratigraphically below the Moss Back Member in the northern part of the swell, but in places they are underlain and overlain by red mudstone of the lower part of the Chinle.

In general, mottled rocks are thin or absent where thick basal sandstones of the Monitor Butte Member or Moss Back Member are present, as in major scour-fill channels. The sparsity of mottled rocks near channel structures has suggested to Johnson (1964) and others that the alteration was older than the channels. However, the fact that jasperoid and carbonate-bearing parts of the altered zone locally crosscut channel boundaries and are found in the basal parts of the channel structures shows that alteration actually was postchanneling.

MINERALOGY

Most of the mottled rocks were formed from red siltstone and claystone of the Chinle and Moenkopi Formations; studies mainly by X-ray methods of both altered and unaltered rocks (Schultz, 1963) indicated that mottled rocks were generally less chloritic and feldspathic but more kaolinitic and contained a mixed-layer clay more montmorillonitic than their unaltered equivalents. Products of alteration that are visible locally in outcrop are jasperoid, hematite, carbonate minerals, barite, kaolinite, sulfides, and uraniferous asphaltite.

The purple color of altered rocks is caused by thin coatings of hematite that is probably more crystalline than the hematite in the red rocks. Keller (1959, p. 117) noted that a purple sample from Dille Butte in the northern part of the swell shows an X-ray pattern that is "* * * more nearly complete for hematite than are those of the hematite-red rocks of the red beds." In purple sandstones the hematite is in fine spherulites which have partly replaced the interstitial cement and detrital grains.

Jasperoid is characteristic of the altered lower part of the Chinle Formation, particularly in the southern part of the swell. It ranges in color from almost white to red, brown, and almost black and forms nodules, tabular vein fillings, and irregular replacement masses. The nodules and replacement masses, like the veins, are generally on fractures. Similar jasperoid, in septarian form, is found in irregularly bleached areas in mainly purplish Chinle mudstone. Microscopically the jasperoid consists mostly of faintly laminated chalcedonic silica.

Carbonate minerals found in the altered rocks are calcite, dolomite, and possibly aragonite. The minerals occur in nodules, fracture fillings, and geodes, and in most places they are localized along partly healed low-angle fractures. Geodes found in the lower part of the Chinle in the Tomsich Butte area have vuggy centers lined with dolomite crystals and rare euhedral quartz crystals. (See also Abdel-Gawad and Kerr, 1963, pl. 2.)

Kaolinite occurs in finely divided form in the silty matrix of the rocks and also in nodules along fractures and vug fillings or in replacement masses in the associated jasperoid. The kaolinite in nodules is locally concentrically banded, and copper sulfides occur in the bands.

Barite occurs as small euhedral crystals in the jasperoid, in irregular masses and nodules in the greenish-gray siltstones, and in euhedral crystals in hematized sandstone. Very small barite nodules in mudstone are stained red by hematite and, as seen in outcrop, are concentrated in linear trends that suggest a fracture control.

Small amounts of sulfides, sulfosalts, and uraniferous and rare-earth-bearing asphaltite are found in bleached areas of the purple-white rocks; they are associated with the jasperoid and more rarely with the carbonate minerals. The metallic minerals identified from the purple-white rocks in the San Rafael Swell and the Orange Cliffs area to the southeast include pyrite, chalcopyrite, sphalerite, chalcocite(?), covellite, tetrahedrite or tennantite, and, at the Lucky Strike mine only, niccolite(?). The copper minerals are generally the most abundant and occur as disseminated grains in jasperoid or in veinlets parallel to or cutting the siliceous material. Delicate laminations in a chalcedonic type of jasperoid bend around chalcopyrite grains and suggest that at least chalcopyrite was deposited at about the same time as the silica.

CHEMICAL NATURE OF THE ALTERATION

Suites of altered and unaltered (or relatively unaltered) rocks were collected by us in the Delta mine area (also near Tomsich Mountain) and by Keller (1959) at the Adams Uranium Co. mine in the northern part of the swell at Dille Butte. Partial chemical analyses of these samples are given in table 1. The A6 and Dille Butte series samples are approximate stratigraphic equivalents; the other samples were collected over a small stratigraphic range, and the rocks sampled were lithologically similar. Analyses of these suites of samples show that red rocks changed into green rocks by loss of iron rather than by the reduction of ferric iron to ferrous iron. The considerable loss of iron in the pale green (white) rocks apparently is partly compensated by an increase in silica (table 1). The altered rocks contain more barium, copper, and certain rare earths than do unaltered rocks (table 6, fig. 13).

X-ray diffraction analysis of purple and white Dille Butte samples showed virtually identical mineralogic compositions, except that the

TABLE 1.—*Partial chemical analyses, in percent, of mudstone of the lower part of the Chinle*

[Dille Butte samples analyzed by Lois Trumbull (in Keller, 1959); all others by D. L. Skinner, J. P. Schuch, and E. C. Mallory, U.S. Geol. Survey]

	Dille Butte area		Delta mine area					
	Suite		Suite 1			Suite 2		
Color of mudstone sample.	Purple	White	Purplish-red	Grayish-purple	White	Red	Purple	White
Field No.	519	520	A6-6C	A6-6B	A6-6A	C3-1C	C3-1B	C3-1D
Laboratory No.	--------	--------	253 301	253 300	253 299	253 104	253 103	253 105
SiO_2	68.03	78.75	64.85	67.69	67.87	58.25	61.22	65.68
Al_2O_3	14.31	13.42	16.97	16.69	17.67	16.43	18.30	14.11
FeO	.10	.04	.23	.23	.11	.50	.29	.32
Fe_2O_3	10.29	1.14	6.31	3.17	1.63	8.69	6.67	1.15
U	--------	--------	.0007	.023	.004	.0004	.0006	.0015

purple sample contained hematite in addition to the quartz and kaolinite common to both samples (Keller, 1959, p. 117). Because both samples had the same clay composition, the assumption was made that there had been no change in clay mineral composition as a result of alteration. Both the white and purple phases analyzed, however, are almost certainly altered equivalents of originally red rocks which were not analyzed; therefore, this conclusion may not be valid. Analysis of the Delta mine area samples suggests that the abundance of kaolinite increases relative to quartz with increased intensity of alteration in the paired A6 samples and with respect to illite or mica clay in the C3 samples (fig. 11).

ALTERED MONITOR BUTTE MEMBER IN THE DELTA MINE AREA

The lower part of the Chinle Formation in the Delta mine area (fig. 19) and in adjacent areas in the southern part of the swell is altered in two zones. The lower zone is about at the Chinle-Moenkopi contact or at the stratigraphic position of a basal Chinle sandstone, the Hunt sandstone of economic usage; the upper zone is about at the position of the medial sandstone of the Monitor Butte Member, the Delta sandstone of economic usage. The scale of alteration is different in the two zones, but the alteration in both is similar chemically and mineralogically.

Alteration in the lower zone affected both the basal part of the Chinle and the uppermost part of the Moenkopi Formation. The alteration zone is present throughout much of the mine area, but it is not present north of the pinchout of the basal sandstone of the Chinle below the Delta mine (section *A–A′*, fig. 19). The most obvious effects of alteration are color mottling of siltstone and mudstone, the presence of secondary hematite in basal sandstone of the Chinle, and the presence of jasperoid nodules and veins in sandstone and mudstone. The color mottling is most conspicuous in the siltstone units where the basal sandstone beds of the Chinle are thin; hematite in the basal Chinle is most noticeable near pinchouts of the sandstone lenses. Jasperoid, which is locally radioactive and sulfide bearing, occurs on low-angle fractures in altered Moenkopi siltstone and in irregular nodular replacements in the Chinle sandstone. It is generally in small masses, but southeast of the Blue Bird mine it is in a bedded vein as

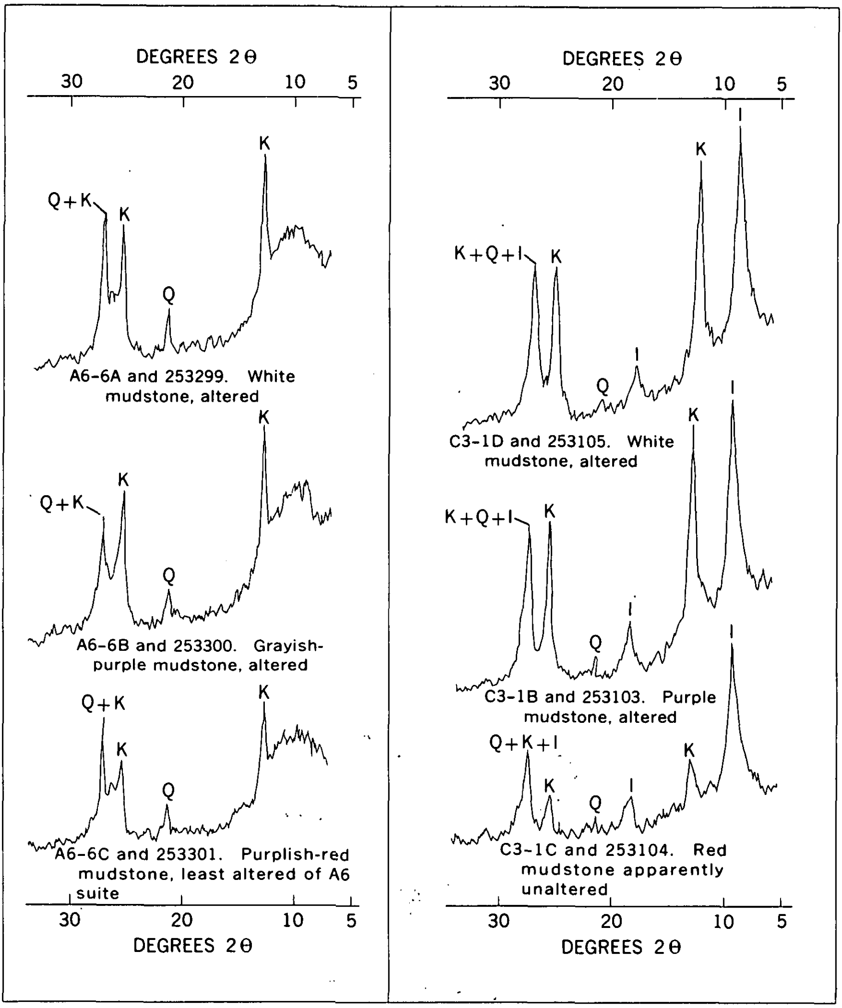


FIGURE 11.—X-ray powder diffractograms of altered and unaltered mudstone, Monitor Butte Member of the Chinle Formation, Delta mine area. Ni-filtered cuKα radiation; K, kaolinite; Q, quartz; I, illite.

much as 3 feet thick at the Moenkopi-Chinle contact. The lower altered zone is the mineralized (uraniferous) zone in the Blue Bird mine.

The upper zone is near the middle of the Monitor Butte Member and can be traced throughout the mine area. It overlies a thin zone of

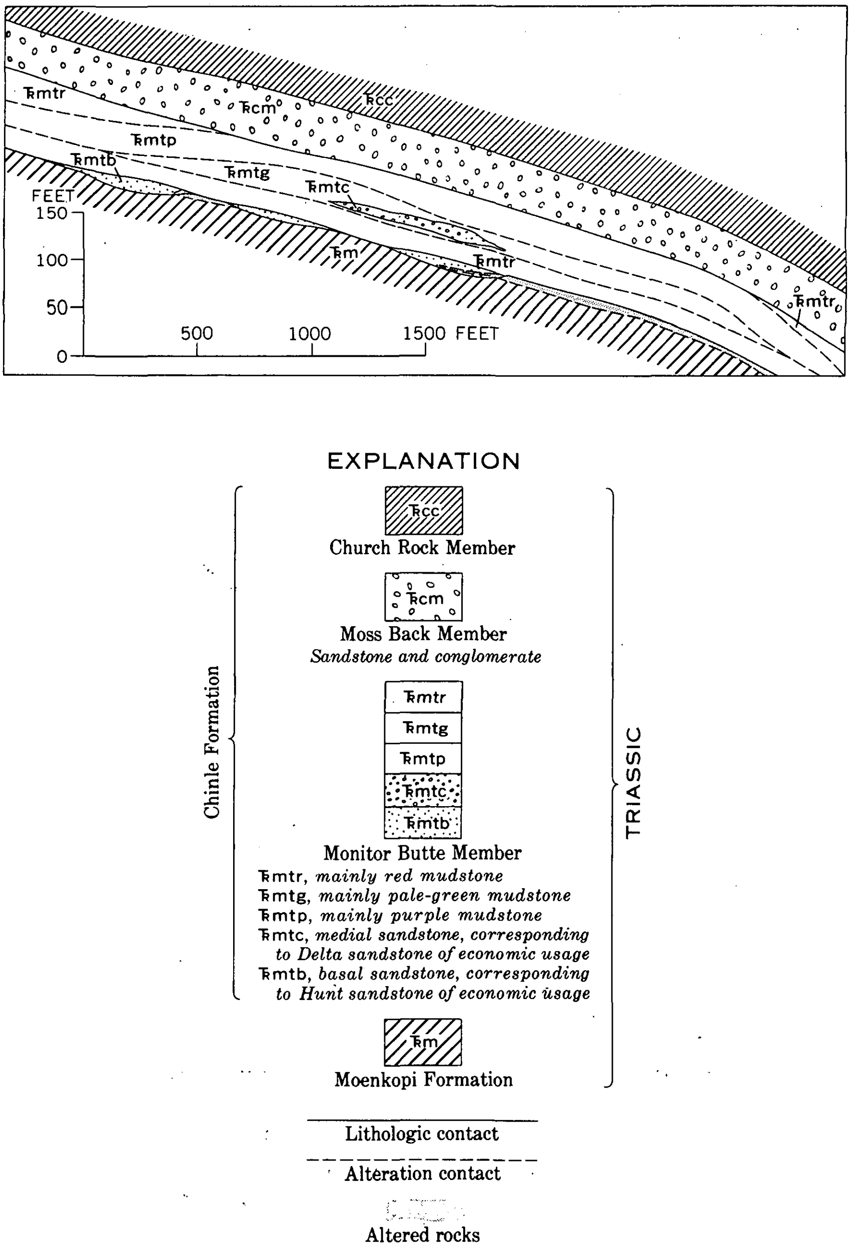


FIGURE 12.—Diagrammatic section showing altered rocks in the Delta mine area.

brownish-red rocks and consists of mainly pale-green rocks that are in turn overlain by purplish rocks. The greenish rocks are about at the stratigraphic position of medial sandstone lenses of the Monitor Butte Member. The green rocks and purple rocks are shown to be altered phases by their small- and large-scale crosscutting relations; south of the Delta prospect adit the color contact between dominantly green and dominantly purple rocks cuts across steeply dipping alternating beds of fine-grained sandstone and siltstone, a condition showing that it is an alteration contact. In a more general way the thickness of the green zone decreases north of the Delta mine and indicates a general crosscutting; the purple zone drops stratigraphically and the upper part of the Monitor Butte Member becomes red (as shown diagrammatically in fig. 12).

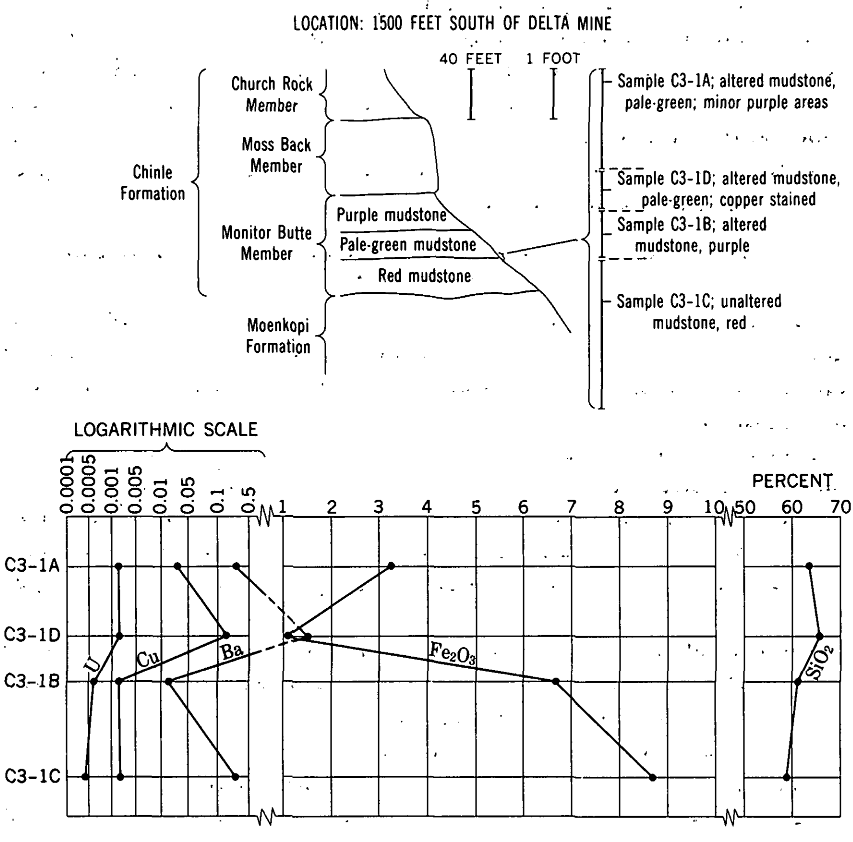


FIGURE 13.—Variation in concentration of some elements in altered and unaltered Monitor Butte Member of the Chinle Formation. Chemical and spectrographic analyses by J. P. Schuch, E. C. Mallory, D. L. Skinner, and Helen W. Worthing.

Large calcareous nodules are found on the lower contact of the pale-green rocks, and this contact also shows abnormal radioactivity, copper minerals, or barite throughout the mine area.

A suite of samples was collected across the red-green contact of the upper zone about 1,500 feet south of the Delta mine. The analyses (plotted diagrammatically in fig. 13) show that the pale-green rocks contain much less ferric iron and more silica than a thin zone of purple rocks at the color contact and also less than the underlying red rocks. Barium, copper, and uranium concentrations are relatively high in the pale-green rocks. Cerium and dysprosium (not shown) concentrations are also somewhat higher in green and purple rocks than in the red rock.

Both upper and lower contacts of the green rocks in the upper altered zone are generally sharp and regular; however, the lower mottled alteration contact is locally irregular because of control by low-angle fractures that occur below sandstone lenses (fig. 14). Chemically the alteration along the fractures resembles the alteration of the whole zone because ferric iron was displaced from the bleached rocks and concentrated as hematite, and copper and uranium minerals were precipitated in the bleached areas.

ALTERED MONITOR BUTTE OR TEMPLE MOUNTAIN MEMBERS IN OTHER AREAS

The alteration zones at the Delta mine can be traced northward on both the east and west flanks of the swell, but their exact relation to altered rocks in the lower part of the Chinle Formation farther north is not known.

The rocks in the upper altered zone north of the mine area are mainly purple, but they contain irregular bleached areas that have coatings of secondary copper minerals. The Little Susan mine northwest of the Delta mine is in a channel-fill deposit in the basal Moss Back Member that is about at the stratigraphic position of the upper alteration zone. Alteration on low-angle fractures, which here occur below the Moss Back Member, is similar to that found on fractures below the medial and lower sandstone lenses of the Monitor Butte Member near the Delta mine (fig. 14).

Near Tomsich Butte the lower part of the Chinle Formation is altered in only one zone. The most intense alteration is just above the Chinle-Moenkopi contact, and mottled and bleached jasperoid-rich rocks grade upward into purple rocks that contain irregular bleached areas with septarian jasperoid. The jasperoid in the purple rocks is similar to that of the mottled zone because it contains a few hundredths to several tenths of a percent of barium and strontium. The purple rocks grade upward into red rocks. Carbonate-rich geodes occur along fractures in the purple rocks.

In the Tomsich Butte area the jasperoid and color mottling were controlled by bedding and fractures; most of the fractures are of the low-angle variety, but nearly vertical fractures at the Green Dragon 3

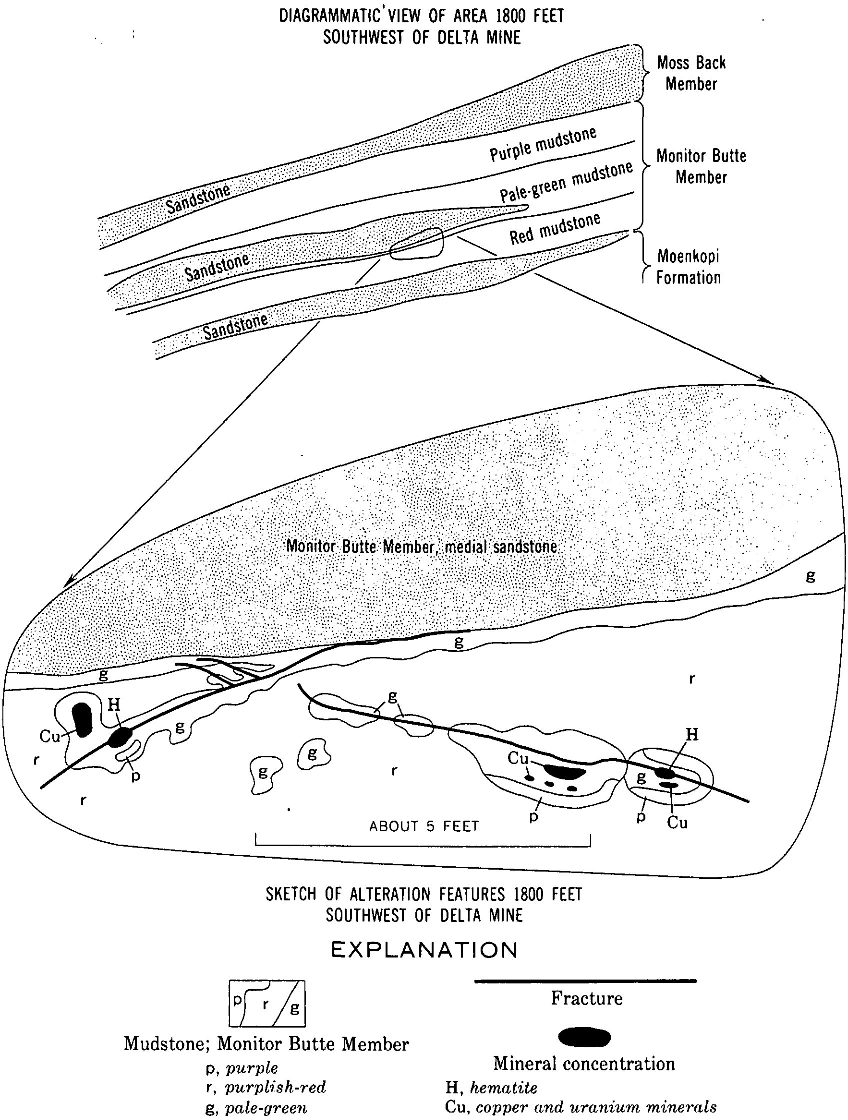


FIGURE 14.—Fracture control of alteration in the Monitor Butte Member of the Chinle Formation, Delta mine area.

claim contain jasperoid. Microfracturing of quartz grains (fig. 15) in the thin sandstone layers of the zone resulted from shearing along the bedding.

On Green Vein Mesa much of the lower part of the Chinle (largely Monitor Butte Member) is bleached, and typical purple-white mottling is rare; however, bedded jasperoid veins like those of the more typically altered areas occur at the Chinle-Moenkopi contact.

Near Temple Mountain the most intense alteration of the lower part of the Chinle Formation was within and just above massive siltstone of the Temple Mountain Member. Color mottling and deposition of jasperoid and carbonates were largely controlled by low-angle fractures in the incompetent mudstone that overlies the competent siltstone and underlies massive sandstone of the Moss Back Member. North from North Temple Wash, jasperoid is not abundant in the purple-white rocks.

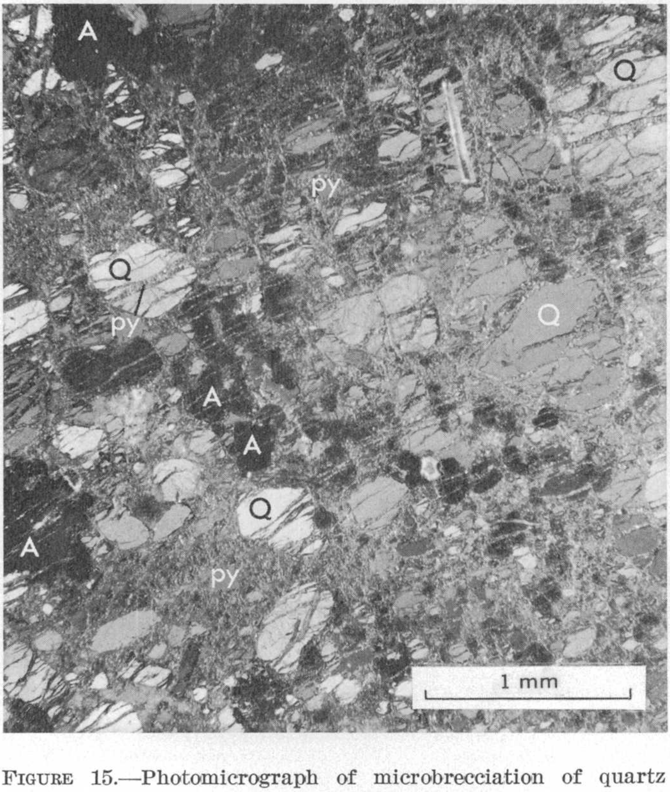


FIGURE 15.—Photomicrograph of microbrecciation of quartz grains in sheared sandstone layer, Monitor Butte Member of Chinle Formation; Q, quartz; A, asphaltite; py, pyrite. Mudstone matrix is pyritic.

In the northern San Rafael Swell the areas with the most highly altered rocks have the greatest amounts of relatively coarse grained quartzose sandstones and conglomerates, rocks that are typical of the Temple Mountain Member in the northern part of the swell.

BLEACHED ROCKS AT THE BASE OF THE MOSS BACK MEMBER OF THE CHINLE FORMATION AND OTHER SANDSTONE-RICH UNITS

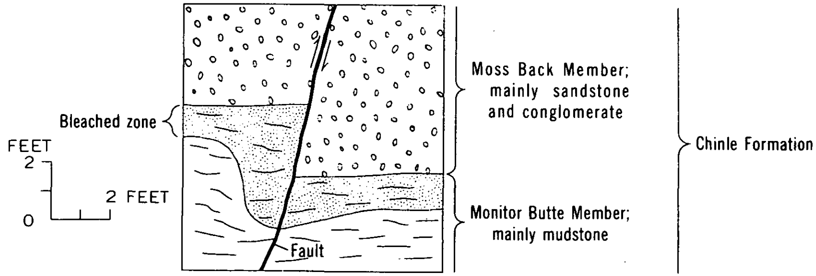
Siltstone and claystone that underlie light-colored sandstone-rich units such as the Moss Back Member, as well as the mudstone "splits" in such units, are generally bleached. Generally the bleached zone below the Moss Back is 1–2 feet thick; its lower boundary parallels the base of the upper unit and faithfully follows scours. Locally the bleached zone thickens along normal faults (fig. 16*A*). In outcrop the bleached zone is commonly gypsiferous and contains scattered limonitic patches; fresh exposures in mines locally show very fine-grained disseminated pyrite in the bleached rocks.

The bleaching is clearly epigenetic as it reflects the form of overlying strata, but its relation in time to the purple-white alteration is uncertain. Bleached zones at the base of the Moss Back near channel structures transgress purple-white rocks (fig. 16*B*), but this relation is probably not diagnostic of age because only the color mottling is truncated, and other features of the purple-white rocks such as jasperoid or carbonate zones continue through the bleached zones.

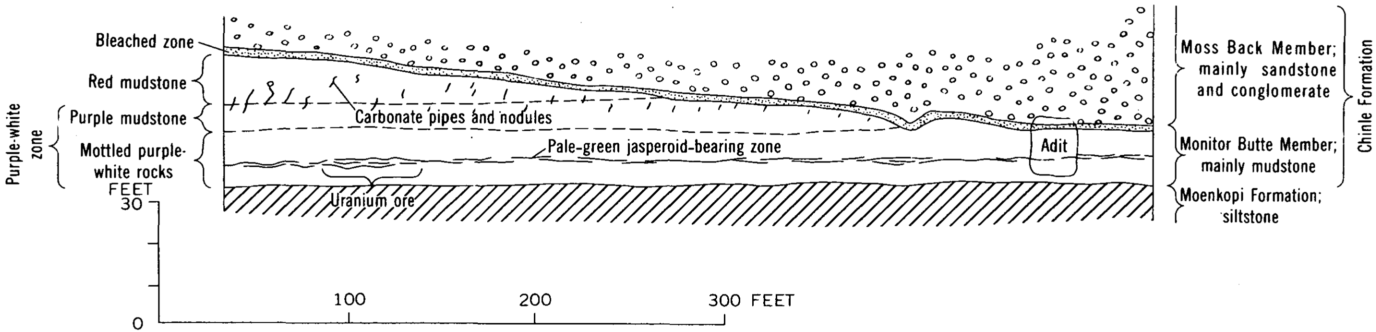
The following partial analysis, in weight percent, of bleached mudstone and red mudstone from the Dexter mine (analysts, D. L. Skinner and E. C. Mallory) shows a small depletion in both Fe^{+2} and Fe^{+3} in the bleached part, but this depletion is insignificant compared with the sharp depletion of iron found in light-colored phases of purple-white altered rock.

	FeO	Fe_2O_3	Al_2O_3	SiO_2
Red mudstone	2. 50	4. 07	13. 78	60. 67
Pale-green (bleached) mudstone	2. 27	3. 90	14. 24	62. 38

In general, studies of red versus bleached mudstone in other areas of the plateau have shown a slight decrease in $Fe^{+3}:Fe^{+2}$ ratio and disappearance of calcite and hematite in the bleached rocks as the only appreciable changes involved in alteration (Garrels and Larsen, 1959, p. 234). As noted previously, the bleached rocks below the Moss Back Member locally contain disseminated sulfides; and from this fact and the general change in $Fe^{+3}:Fe^{+2}$ ratio cited by Garrels and Larsen, it is inferred that some reduction of ferric iron was generally involved in this type of alteration. In some places, as perhaps at the Dexter



A. SKETCH OF AREA ABOUT 2 MILES WEST OF DELTA MINE



B. SKETCH AT GREEN DRAGON 3 MINE, SOUTH FLANK OF GREEN DRAGON 3 SCOUR CHANNEL

Geology by C. C. Hawley and J. G. Moore, 1956

FIGURE 16.—Relation of bleached zone below the Moss Back Member to fault (*A*) and purple-white zone (*B*).

mine, the alteration probably reflects a change only in the location of iron, such as from hematite coatings on the grains in the red beds to clay minerals in the bleached beds.

ORIGIN OF THE PURPLE-WHITE AND BLEACHED ROCKS OF THE CHINLE FORMATION

Both purple-white alteration and bleaching probably are epigenetic, although the origin of the purple-white rocks in particular is controversial and has previously been explained by other hypotheses. Schultz (1963), Johnson (1957), and Finch (1959) favored a syngenetic origin; they noted the general coincidence of the purple-white altered zone with the mid-Triassic unconformity and proposed that the zone formed at the surface, principally by weathering. The late H. B. Dyer, a coauthor of the present report, proposed (written commun., 1954) that the altered zone was of diagenetic origin and that it formed before most other alteration and before the ore deposits.

Recently Abdel-Gawad and Kerr (1963) have proposed that purple-white altered rocks and uranium ore are results of related epigenetic processes. Previously others, including Finch (1953 a, b), McKeown and Hawley (1956), and McKeown, Orkild, and Hallagan (1956), had recognized a regional relationship between purple-white altered rocks and uranium deposits and a local relation, at least, between altered rocks and ore. Each of the three hypotheses—syngenetic, diagenetic, and epigenetic—have aspects that recommend them. In contrast, only an epigenetic hypothesis can seriously be entertained for the thin zones of bleached rock that underlie most sandstone-rich units, particularly those of the Chinle Formation, because of their conformable relation to the overlying units.

Genetically important characteristics of the bleached zones below the Moss Back Member include conformable relation to the overlying strata, sparse mineralogic and chemical differences relative to adjacent red strata, and wide geographic distribution. Bleached zones are found not only below ore-bearing parts of the Moss Back but also under light-colored barren facies. These characteristics suggest that the conformable bleaching is mainly due to mildly reducing connate fluids present in the Moss Back. These fluids could have been waters associated with coals and petroleum in the Moss Back, or perhaps they could have been petroleum itself or associated sulfur-bearing gases. The bleaching could have happened at any time after deposition of the overlying strata and perhaps did not take place everywhere at the same time. As pointed out earlier, some bleaching followed normal faulting, and some could have accompanied ore deposition in the Moss Back.

Characteristics of the purple-white rocks that seem to be genetically important include very wide distribution near the base of the Chinle Formation, nearly stratiform distribution and partial control by low-angle fractures, strongly kaolinitic character, and mineralized jasperoid content. The abundance of Fe^{+3} in unaltered and purple rocks and the sparsity of either Fe^{+3} or Fe^{+2} in the white rocks must also be explained.

The wide distribution of purple-white rock at or near the mid-Triassic unconformity on the Colorado Plateau has suggested a weathering origin to Johnson (1957), Finch (1959), and Schultz (1963). However, this distribution can also be explained diagenetically or epigenetically; and even though there is a gross relation of altered rocks to the basal Chinle, the altered zones do not conform in detail to either the main hiatus between the Moenkopi and the Chinle or minor unconformities. In the San Rafael Swell they seem more closely related to epigenetic zones of bedding-plane shearing. Other criteria consistent with a diagenetic or later origin are the upward as well as downward gradation into unaltered rocks (Schultz, 1963, p. C43) and the cross-cutting of the jasperiod and carbonate zones into stratigraphically higher units in scour-channel structures.

The chemical nature of the alteration seems most consistent with weakly acid solutions that were oxidizing relative to the Fe^{+3}–Fe^{+2} transformation. These solutions probably were only partly connate. Weakly acid solutions are favored because they have the ability to displace ferric iron (Garrels and Richter, 1955, p. 454) and because they explain the observed pattern of silicification and carbonatization. The alteration of feldspars to clay minerals and the transformation of illite and montmorillonite to kaolinite observed in the altered rocks would be favored by the excess hydrogen ions of such solutions. Under this hypothesis silica that was freed in the hydrolytic alteration was reprecipitated as jasperoid in the strongly leached (pale-green) rocks; carbonates were precipitated along the border of the zone of most intense leaching because of the consumption of hydrogen ions in the alteration process and the consequent breakdown of soluble bicarbonate complexes. The abundance of hematitic rocks in Monitor Butte and Temple Mountain Members and the sparsity of organic materials indicate that fluids characteristic of these units would be relatively oxidizing. However, if the proposed mechanism of alteration is valid, it is probably necessary that extrinsic components, such as carbon dioxide, be added to acidify the connate solutions because the intrinsic solutions of the claystone-rich units would likely be alkaline in reaction after diagenesis (Garrels, 1957).

The nearly stratiform distribution of the altered-rock zones indicates that the solutions causing alteration mainly moved laterally. This movement through mudstone-rich rocks was facilitated by a secondary permeability caused by bedding-plane and related low-angle fractures and, where sandstone lenses were present, by a primary permeability due to lithology.

The relation of the altered zones to ore is discussed later in the report, but it is pointed out here that the purple-white zone contains weakly mineralized rock at many places and in at least one place in the swell, the Green Dragon 3 mine, a jasperoid-rich part was ore and was mined.

ALTERED ROCKS IN THE GLEN CANYON GROUP

Rocks of the Glen Canyon Group which are high structurally on the San Rafael anticline are bleached yellowish-white to tan, which contrasts with the pale-orange and red of the Glen Canyon rocks exposed structurally lower on the anticline (fig. 9). Red and white rocks are exposed together at places on the southern, southwestern, and northern parts of the swell and also on the northeast flank. The rocks that crop out on the northwest flank are all relatively high on the anticline and are bleached. Near Temple Mountain on the southeast flank, the bleaching is pervasive and nearly all the exposed Glen Canyon rocks are light colored. In places, as at the exit of Muddy Creek from the swell near the Delta mine, the color contact is a planar feature that is nearly level (the bedding dips from about 10° to 18°) with red rocks below the color contact and white above. At the entrance of Muddy Creek near Tomsich Butte, the red phases intertongue with white, but the amount of red rocks increases downdip.

The red sandstones contain hematite in thin films on sand grains; the white rocks, at least near the surface, are speckled with limonite that probably formed from oxidation of either pyrite or ferruginous carbonates that were present in the more deeply buried rocks. Analyses of two suites of paired red-white Wingate samples disclosed no appreciable differences in equivalent uranium or percent total iron.

The bleached rocks contain small masses of dolomite-impregnated rocks and micaceous silicates that are abnormally green, a condition suggesting the presence of some chromium. The bleached rocks are locally petroliferous, but only on Temple Mountain are they consistently petroliferous. The petroliferous areas are embayed and veined by bleached areas, and so some bleaching is inferred to have taken place after introduction of petroleum.

The occurrence of the bleached rocks on the higher parts of the swell and the crosscutting contact show that the bleaching took place after folding of the San Rafael Swell. The continuity of the regionally bleached rocks with the pervasively altered rocks at Temple Mountain and the similarities in the alteration—that is, secondary dolomite, altered micaceous silicates, and removal of petroleum—suggest that the regional alteration took place at the same time as intense rock alteration and uranium mineralization at Temple Mountain.

ORE DEPOSITS

Most of the ore deposits of the San Rafael Swell are uranium deposits in sandstone and conglomerate of the Chinle Formation. Besides uranium, they contain vanadium, copper, zinc, lead, and molybdenum in anomalous amounts; copper and vanadium are recovered from some ore. That the deposits are epigenetic is shown by the fact that the introduced valuable minerals replaced detrital grains and their cementing materials; also, the boundaries of the ore locally cut across the bedding and other primary features of the rock. The amount of replacement that occurred in ore deposition varied widely: in low-grade ore, the valuable substances are mostly interstitial to detrital grains and evidently replaced only the interstitial material; in high-grade ore, only remnants of the original rock are left, and replacement was extensive.

The ore bodies commonly show a close relation to the lithology of the host rocks, and control of ore deposition by primary or diagenetic features of the rocks was important. But the ore bodies also show relations to later features such as bedding-plane faults, collapse structures, and folds, and thus their localization was complex.

DISTRIBUTION OF DEPOSITS

Uraniferous rocks have been found in the Coconino Sandstone, Kaibab Limestone, Moenkopi Formation, Chinle Formation, Wingate Sandstone, and Navajo Sandstone. Most of the uranium deposits are in the Chinle Formation; and except at Temple Mountain, deposits in other units are distributed sporadically.

Most deposits lie in three geographic belts (inset, pl. 1). The South belt contains all the large uranium deposits of the swell except those at Temple Mountain. The North belt contains a few small mined ore bodies and several bodies of mineralized rock. The very small Temple Mountain belt contains the larger uranium deposits of the Temple Mountain district. Weakly uraniferous rocks and small deposits are found in the areas between the belts, but prospecting has been extensive enough to show that deposits are more numerous and larger in the belts of favorable ground.

The South belt's north boundary is inferred to have extended northwestward across the swell from a point between Temple Mountain and

Chute Canyon on the east side of the swell to about the north end of Green Vein Mesa on the west; its south boundary is not exposed. This belt is inferred to extend southeastward under the younger rocks that crop out on the Green River desert and to be continuous with the southern belt of uraniferous occurrences in the Orange Cliffs area that were recognized by McKeown and Orkild (1958, fig. 7). The North belt probably projects toward the northern belt of favorable ground of McKeown and Orkild.

The exposed boundaries of the South and North belts are defined partly by the thickness and lithologic character of the Temple Mountain, Monitor Butte, and Moss Back Members of the Chinle Formation. The belts coincide with areas of relatively thick combined Monitor Butte and Temple Mountain Members and relatively thin Moss Back Member (pl. 1, fig. 4). The South belt coincides generally with well-formed scour-fill channels of the Moss Back Member, such as the Tomsich Butte channel. The lower part of the Chinle of the belt, mainly the Monitor Butte Member, locally contains lenslike channels, as at the Delta mine. The North belt coincides with channel deposits of the Temple Mountain Member.

Purple-white alteration of the combined Monitor Butte and Temple Mountain Members is conspicuous in both North and South belts but not in the intervening area, particularly where the underlying Moenkopi Formation is completely bleached. Jasperoid also appears to be very sparse north of Temple Mountain on the southeast flank of the swell and on Green Vein Mesa on the west flank.

The Temple Mountain belt is about 2,000 feet downdip from the Temple Mountain collapse, and it parallels structure contours of the Temple Mountain area. Although the Temple Mountain district is only a short distance north of the mines of the South belt, it has not been included as part of the South belt because its ore deposits are different in chemical composition, mineralogy, form, alteration, and control, and the deposits were probably formed at a slightly later time.

In the Chinle Formation of the San Rafael Swell, uranium deposits are found principally in the Monitor Butte and Moss Back Members; but occurrences of mineralized rock are numerous in the Temple Mountain Member, and a very few small uranium deposits occur in the Church Rock Member. Except at Temple Mountain, most deposits in the Chinle are within 30 feet of the Chinle-Moenkopi contact and occur in the basal parts of channel deposits. At Temple Mountain the deposits are commonly about 50 feet above the contact and occur "floating" in medial units of the Moss Back.

The deposits of the South belt occur either in sandstone lenses of the Monitor Butte Member, in scour-channel deposits of the Moss Back cut into the Monitor Butte Member, or rarely in the underlying Moenkopi Formation. The deposits and mineralized rocks of the North belt are in the Temple Mountain and Moss Back Members. The uraniferous rocks occur in the basal parts of channel structures of the favorable units, except at the Dexter 7 mine where they occur in two stratigraphic positions in the Moss Back. At Temple Mountain all the large deposits and many small ones are found in the Moss Back Member; the combined Monitor Butte and Temple Mountain Members are only weakly mineralized.

In the Temple Mountain district small ore deposits, or abnormally uraniferous rocks, are found in the Coconino Sandstone, Kaibab Limestone, Moenkopi Formation, Church Rock Member of the Chinle, and Wingate Sandstone as well as the Moss Back Member of the Chinle. The deposits in units other than the Moss Back Member are in or near collapse structures. Scattered crystals of galena and other sulfides are apparently widespread in the Sinbad Limestone Member of the Moenkopi Formation in the Temple Mountain district. Sandstones of the Church Rock Member also are abnormally radioactive near some faults in Lane Wash in the northwestern part of the swell, and the brecciated Church Rock Member and Wingate Sandstone are uraniferous at the Little Joe collapse. The Navajo Sandstone is the host rock for weakly uraniferous deposits formerly prospected for copper at the Copper Globe mine in the west side of the swell.

SIZE OF THE ORE BODIES

The ore bodies in the South mineral belt range in size from those that contain only a few tons of ore to the Delta ore body that contained more than 100,000 tons. Typical ore bodies of the belt—as in the Dirty Devil 3, 4, and 6 mines, the Cistern mine, and probably the Conrad mine—range in size from 1,000 to 5,000 tons. A single ore body in the Lucky Strike deposit, which is next largest to the Delta ore body, contained more than 10,000 tons. Single ore bodies on Green Vein Mesa are small, but groups of closely spaced ore bodies may contain as much as 1,000 tons.

The ore bodies are as much as 600 feet long and 20 feet thick, as in the Delta mine. The average thickness of the Delta ore body was about 10 feet, which is approximately the maximum thickness of other ore bodies in the South belt. Although the Green Vein Mesa ores average only about 2 feet in thickness, their relatively high grade locally makes selective mining possible.

Ore bodies in the Temple Mountain mineral belt, which contain 10,000 tons or more of ore, include some in the Calyx 3, 8, and 12 mines, North Mesa 2 mine, and Vanadium King 1 mine (pl. 1). Deposits near Temple Mountain, but outside the belt, are smaller, but they may contain as much as 2,000 tons. Individual ore bodies in the Temple Mountain belt have been traced for as much as 700 feet; they are as much as 15 feet thick but average about 5 feet in thickness.

The most productive mine outside the South and Temple Mountain belts has been the Dexter 7 mine, on Calf Mesa in the northern part of the swell, which has produced more than 500 tons of ore. Several other mines have been opened around Calf Mesa, but drilling by the U.S. Atomic Energy Commission appears to show that the ore bodies are small. Some early drilling indicated ore bodies of considerable extent, but offsetting showed that the ore bodies, although numerous, had little horizontal extent.

SHAPE OF THE ORE BODIES

Most of the uranium ore bodies in the San Rafael Swell are either in the form of rolls or are tabular, but a few small ore bodies are veinlike, pipelike, or irregular in form. Rolls (Fischer, 1942; Shawe, 1956) are a common type of ore body of the Colorado Plateau, although they apparently are more typical of deposits in Jurassic host rocks such as the Morrison Formation or the Entrada Sandstone than they are of deposits in Triassic host rocks. Ore rolls generally have a crescent shape in cross section, although in some cross sections the shapes are very complex. Rolls typically are more elongate in plan than the tabular deposits, and they commonly are elongate parallel to the direction of sedimentary structures. At least one contact of a roll ore body cuts or "rolls" sharply across the bedding, and at this contact ore abuts sharply against altered but nearly barren rocks. The other contact is generally gradational into unaltered rock, but it may also be a crosscutting contact. According to Shawe (1956), rolls are most likely the result of interface phenomena between two liquids with different properties.

The roll deposits of the Temple Mountain belt are elongate bodies with a length-to-width ratio of 10:1 or more. They commonly trend northwestward or about at right angles to the belt. Some rolls have a paired mirror image ore body at about the same stratigraphic position; the paired ore bodies are separated by barren, but altered, rocks. The cross-sectional shape of individual roll ore bodies characteristically changes in the long direction of the ore body; one of the larger ore bodies in the Calyx 8 mine in the Temple Mountain district changes downdip from a roll to a large blanket or tabular deposit.

Small rolls are also found in deposits in the South mineral belt and in the northern part of the swell. A small roll 2–3 feet across is exposed in the back of the Little Susan mine and roll-like concretionary masses of similar size occur in the Delta mine. Ore in the upper adit of the

Dexter 7 mine has a crosscutting roll-like contact, and ore in this mine also occurs in vertical pipes about 6 inches across.

Tabular deposits, which are nearly parallel to the bedding of the sedimentary rocks, are generally somewhat oval in plan; many are elongate in the direction of a controlling sedimentary structure (generally a minor erosional scour), but very few have a length-to-width ratio exceeding 2:1. Most ore bodies in the South mineral belt and a few in the Temple Mountain mineral belt are tabular. Typical tabular deposits exposed in the Dirty Devil 4 and 6 mines and in the Lucky Strike mine.

LOCALIZATION OF ORE

The uranium deposits of the San Rafael Swell were localized by a combination of lithologic and structural features which are discussed in two groups: (1) the features that localized individual ore bodies, and (2) those that localized groups of ore bodies and mineral belts. Single ore bodies reflect control by channel structures, bedding, bedding-plane fractures, and probably cementation and organic content of the host sandstone, but the relative importance of these and other controls is still uncertain. The factors of localization of groups of ore bodies and belts of deposits are more uncertain, although in the Temple Mountain district it can be shown that the main belt of deposits closely correlates with structure of that area. The North and South belts of deposits lie approximately on the flanks of the old northwest-trending anticline; this distribution suggests that the old anticline was a control of mineralization. But did it exert a direct structural control or only an indirect one because this structural feature influenced the thickness and lithology of the ore-bearing units? It has also been found that most of the main ore deposits of the South belt are near fold axes, but with the present data it is impossible to say whether this is significant genetically or whether it is only coincidental.

LOCALIZATION OF SINGLE ORE BODIES

Ore bodies are localized by sedimentary structures, of which the most obvious are the channels of the Chinle Formation, and by tectonic structures. All three types of channels previously described (p. 23)—scour, lens, and intraformational—are locally ore bearing.

In the South belt the ore deposits of the Moss Back Member are in scour-type channels; typical examples occur at the Cistern, Dirty Devil, and Lucky Strike mines. Details of the scour at the Dirty Devil 3 and 4 mines are shown on plate 6. The deposits in the Monitor Butte Member are in lens channels, although small local scours at the base of these sandstone bodies may further localize ore, as in the Delta mine (Keys, 1954, fig. 8, 105 drift) and Hertz mine (fig. 23). Lens channels also localize mineralized rock in the Temple Mountain Member in the North belt. At Temple Mountain the bulk of the ore lies in intraformational channels of the medial massive sandstone unit of the Moss Back Member.

Lithologic character and small-scale sedimentary structures also influenced distribution of ore. The largest and richest ore bodies are in fine- to medium-grained sandstones that are weakly to moderately cemented with calcite or clay minerals; the favorable sandstones contain scattered woody materials, and, in many places, petroleum. These sandstones are found in the Monitor Butte and Moss Back Members and are well mineralized at the Delta mine, in the Temple Mountain district, and on Green Vein Mesa. According to Keys (1954, p. 14), the most consistently mineralized zone in the Delta mine was a thin fine-grained micaceous sandstone within the medial sandstone lens of the Monitor Butte.

Bedding planes and mudstone "splits" apparently exerted a confining effect on mineralization. This confinement is particularly noticeable in the Temple Mountain district where the ore-bearing sandstone lenses are commonly capped and floored with mudstone-rich rocks; only in the places where the mudstone splits thin do the ore bodies cross from one sandstone lens to another.

Tectonic structures that controlled ore distribution were principally bedding-plane fractures and, near collapse structures, small high- and low-angle fractures. Bedding-plane and associated low-angle faults are found particularly in the lower part of the Chinle Formation at sandstone-siltstone or siltstone-mudstone contacts; locally these fractures contain jasperoid, sulfides, and uraniferous asphaltite. Mineralized shear zones were noted at the Dirty Devil 4 and Lucky Strike mines at the base of the Moss Back Member and also at the Green Dragon 3, Dolly, and Pay Day mines in the Monitor Butte Member. In the Dirty Devil mine the shear zone was a highly uraniferous streak just below the Moss Back; the zone was mined together with overlying sandstone of lower grade. At the Green Dragon 3 mine the shear zone, mainly in siltstone, was mined by itself as uranium ore. In the Dolly mine a copper-rich uranium deposit, pyrite or marcasite, and copper sulfides and sulfosalts are the main introduced components of the sheared rock.

Evidence that bedding-plane shearing may have localized a large ore body is found at the Delta mine, where the sandstone lens that is the host rock for the ore body is at the stratigraphic position of altered siltstone which can be traced laterally for thousands of feet away from the ore body. The base of the altered zone coincides with a weakly radioactive zone of bedding-plane fractures, whose radioactivity indicates that uraniferous solutions migrated along the zone.

Ores controlled by both high- and low-angle faults and fractures are found in and near the Temple Mountain collapse (Hawley and others, 1965) and in the Little Joe collapse. Rarely, high-angle faults away from collapse areas have been mineralized. On Calf Mesa, high-angle northwest-striking faults are reported to contain copper minerals and to be radioactive (R. L. Akright, written commun., 1953). On Green Vein Mesa a north-striking fault contains barite, which is relatively abundant in the uranium ores of the mesa; this fact may indicate that the fault is older than the ore.

LOCALIZATION OF GROUPS OF ORE BODIES AND BELTS OF FAVORABLE GROUND

The South mineral belt coincides areally with scour-type channels of the Moss Back Member and with conspicuous purple-white altered rocks of the Monitor Butte and Temple Mountain Members. The mineral belt is on the southwest flank of the belt of completely bleached Moenkopi Formation which in turn coincides with an ancient northwest-trending anticline. That tectonic structures as well as lithology may have helped localize the deposits is suggested by the relation of deposits to minor folds and by the relation of deposits in channels to zones of altered, sheared rock. The relation of deposits to folds is suggested in the southern swell area, where all medium to large deposits, except the Cistern mine, are near the axes of folds (fig. 17). Possibly this relation is coincidental, however, because all the deposits are in channel structures. The relation of deposits to sheared, altered rocks of the purple-white zones is more definite. Although the deposits of the South belt are in scour or lens channels, many such channels are only weakly mineralized if mineralized at all. A common factor of productive channels seems to be that they intersect a zone of sheared, altered rocks, now indicated by the purple-white zones (fig. 18). Where two sheared and altered zones are present, as in the Delta and Blue Bird mines of the southern swell, mineralization can occur in both zones. Where there is only one zone, ore occurs at only one horizon. As drawn, figure 18 approximates the southwest flank of the swell, the left side representing the Delta area south and the right side Tomsich Butte north. The ore in the scour channel of Moss Back, shown near the center of the figure, approximates the ore occurrence at the Little Susan mine.

The North belt of deposits coincides with a part of the Temple Mountain Member which has lens-type channels; the rocks in these channels are altered, and the channel structures probably contributed to the location of the belt.

At Temple Mountain there is good evidence of structural control of the belt of main deposits. The belt parallels local structure, and it lies just structurally above the anticlinal bend of the monocline along the east flank of the swell. Small ore bodies are found between the belt and the Temple Mountain collapse, but ores have not been found downdip from the belt.

MINERALOGY

The ore deposits consist of the detrital minerals and substances of the sedimentary host rocks and the metallic, nonmetallic, and carbonaceous materials introduced diagenetically or later into the sedimentary rocks. In most ores the detrital components are much more abundant than the introduced ones. The introduced components of the unoxidized ores are principally uraninite or the uraniferous carbonaceous mineraloid, asphaltite, more rarely, coffinite; and one or more of the common base metal sulfides, pyrite, galena, sphalerite, chalcopyrite, and chalcocite(?). Low-valent vanadium minerals are abundant in the unoxidized ores of the Temple Mountain district and probably occur locally in other deposits. Introduced nonmetallic minerals include jasperoid, carbonates, and barite. Both metallic and nonmetallic minerals of the unoxidized ores and the introduced carbonaceous materials are discussed under "Primary minerals." The deposits locally contain sparse to abundant higher valent minerals, the secondary minerals, which formed during near-surface weathering and oxidation of the primary ore. The most common of these secondary minerals are carnotite, zippeitelike minerals, metazeunerite, and torbernite or metatorbernite.

PRIMARY MINERALS

The primary minerals introduced at least locally into the deposits are divided into five groups: (1) sulfides, arsenides, selenides, and sulfosalts, (2) oxides, (3) sulfates and carbonates, (4) silicates, and (5) carbonaceous materials. The uranium in unoxidized deposits occurs as uraninite (an oxide), as coffinite (a silicate), and in asphaltite (a carbonaceous mineraloid).

SULFIDES, ARSENIDES, SELENIDES, AND SULFOSALTS

Sulfide minerals in the deposits, in approximate order of decreasing abundance, are pyrite, sphalerite, galena, chalcocite(?), chalcopyrite, marcasite, molybdenite(?), bornite, covellite, and bravoite.

Pyrite (FeS_2) is the most common metallic mineral. It is found in most nonhematitic rocks, and in many occurrences it is apparently

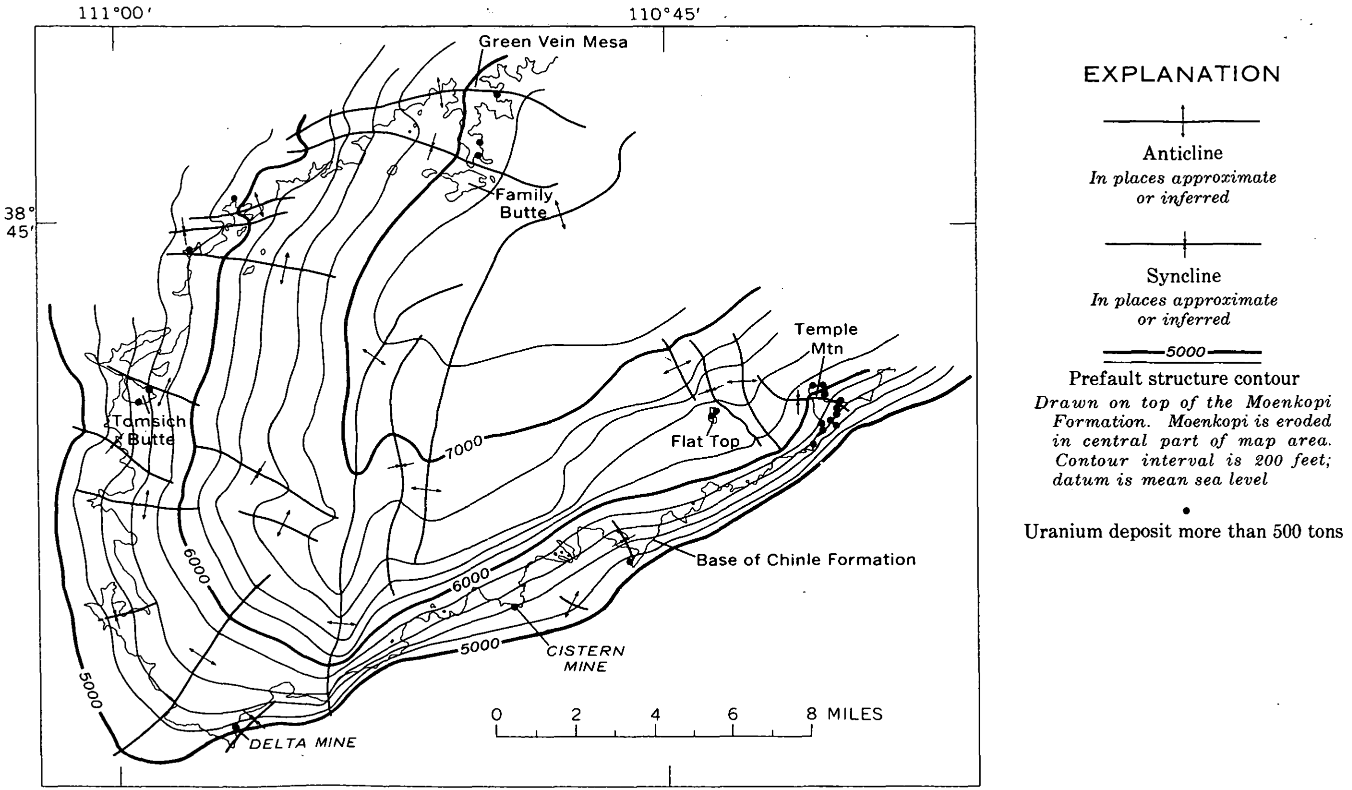


FIGURE 17.—Relation of larger uranium deposits to prefault structure in the southern part of the San Rafael Swell.

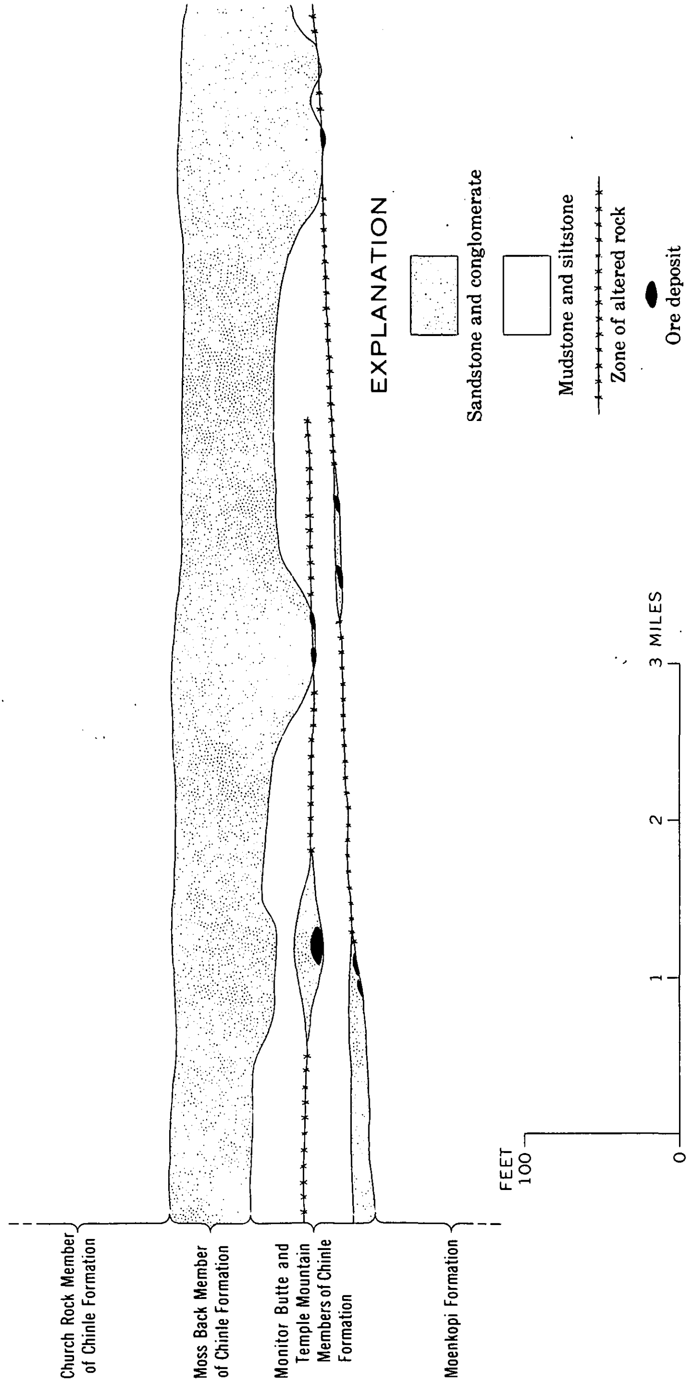


FIGURE 18.—Diagrammatic sketch showing relation of ore deposits to zones of altered rocks.

not related to the uranium mineralization. In fine-grained rocks such as siltstone, the pyrite is in small discrete cubes or pyritohedra, or in anhedral nodular masses; in sandstone it is in crystalline to massive interstitial fillings and nodules. Pyrite is found with coaly materials in both sandstone and mudstone; in coal the pyrite is present as irregular replacements or cavity fillings, in veinlets, or in the plant cell structure.

Very fine grained zoned pyrite is disseminated in the ores formed at about the same time as uraninite and other components of the ores. This type of pyrite has been observed in ore from the Temple Mountain area, the Dexter 7 mine, the Lucky Strike mine, and the Delta mine. At the Lucky Strike mine pyrite is zonally intergrown with chalcopyrite in the bleached mudsone just below the ore; at the Delta mine fine-grained pyrite-bravoite intergrowths are associated with fine-grained uraninite.

Sphalerite (ZnS) is common in some of the ore but is likely to be overlooked. It occurs as microscopic grains in ores of the Temple Mountain district and as disseminated fine- to medium-grained anhedral grains at the Dirty Devil, Conrad, and Lucky Strike mines. At the Dirty Devil 4 mine a sphalerite zone borders jasperoid masses in conglomerate. All the sphalerite observed is a light-tan-yellow color.

Galena (PbS) is a common component of some of the ores. It is relatively abundant in the southern part of the Delta ore body and in the Dirty Devil, Conrad, and Lucky Strike mines. It is found in small amounts in most Temple Mountain ores but is abundant only at depth in the Temple Mountain collapse. Single small crystals of galena are found in the Sinbad Limestone Member of the Moenkopi Formation over much of the Temple Mountain district.

Galena is particularly abundant in the southern part of the Delta mine and forms coarse crystals associated with massive uraninite in coalified wood. It also occurs in woody material in the Dirty Devil and other mines in the Moss Back Member of the west side of the swell, but in these mines galena also occurs as poikiloblastic crystals that enclose detrital grains. The galena in the Delta, Dirty Devil, and Lucky Strike mines seems to be concentrated peripherally to the concentrations of uranium minerals.

Chalcocite (Cu_2S), a general mineral name that includes djurleite and probably digenite, and chalcopyrite ($CuFeS_2$) are the most common copper sulfides. Both minerals occur in trace amounts in the altered rocks and jasperoid of the Temple Mountain and Monitor Butte Members. Chalcocite is abundant in the Cistern mine and also in mineralized rock from the North Reds Canyon collapse structure. Chalcopyrite is relatively abundant in the copper-rich ores of the Green Vein Mesa area and also in the Cistern mine; it is locally abundant in the Lucky Strike mine.

Marcasite (FeS_2) occurs locally in woody material in a manner similar to pyrite. In some deposits outside the Temple Mountain area, it is more closely associated with copper and uranium minerals than is pyrite. Marcasite is locally in ores from the Dirty Devil, Lucky Strike, and Dolly mines; it probably occurs in the Little Susan and Cistern mines. It is partly disseminated but also occurs as veinlets in fractured mudstone underlying ores at the Lucky Strike and Dirty Devil mines and in sheared sandstone at the Dolly mine. At the Dirty Devil and Dolly mines, the marcasite is at least in part younger than the associated chalcopyrite and tetrahedrite-tennantite.

Molybdenite(?) (MoS_2) or a related low-temperature mineral has been found at the Lucky Strike mine and probably occurs in other mines on the southwest flank of the Swell.

Bornite (Cu_5FeS_4) and covellite (CuS) are sparse in vanadium-uranium deposits in the Wingate Sandstone at Temple Mountain, and covellite was reported by Keys (1954) from the Delta mine. Gott and Erickson (1952, p. 6–7) reported minute blebs of chalcopyrite, chalcocite, and covellite in carbonaceous material from the Dalton claims on Calf Mesa and bornite, chalcopyrite, covellite, and chalcocite in uraniferous carbonaceous materials from claims in the SW¼ sec. 20, T. 23 S., R. 10 E., on Green Vein Mesa.

Bravoite ($(Fe, Ni)S_2$) occurs in fine-grained intergrowths with pyrite at the Delta mine.

The arsenide group is probably represented by niccolite ($NiAs$), which was tentatively identified (by its appearance in polished section and by microchemical tests) in radioactive red jasperoid in altered Monitor Butte Member at the Lucky Strike mine. Cobalt- and nickel-bearing minerals from deposits on Green Vein Mesa were also reported by Gott and Erickson (1952).

One selenide mineral, ferroselite ($FeSe_2$), has been found in the Temple Mountain district. The ferroselite occurs mainly in small disseminated grains peripheral to asphaltite-rich uranium-vanadium ore.

Tetrahedrite-tennantite ($Cu_6Sb_2S_6$-$Cu_6As_2S_6$) occurs sparsely in ore and mineralized rock in the Wingate Sandstone at Temple Mountain. It also occurs sparsely in ores on Green Vein Mesa and at the Dexter 7 mines on Calf Mesa.

OXIDES

Oxides introduced into the deposits are the ore minerals uraninite and montroseite, and locally a gangue mineral, hematite. Uraninite (ideally UO_2, generally $(U^{+4}_{1-x}, U^{+6}_{x})O_{2+x}$, from Frondel, 1958, p. 13) is probably the primary uranium mineral; it occurs in massive form, typically as a replacement of carbonized wood, and in very finely divided form in uraniferous asphaltite. Relatively coarse uraninite was found at the Delta, Pay Day, Magor, and Lucky Strike mines; in nearly all other mines and in most of the Lucky Strike mine, the uraninite is finely divided and found with asphaltite.

At the Delta mine some coalified logs were nearly completely replaced by uraninite; although some coaly material outside the ore zones is barren, logs in the ore zone contain as much as 83.5 percent U_3O_8 (Keys, 1954, p. 19).

Montroseite ($VO(OH)$) or its alteration product, paramontroseite, is found in unoxidized vanadiferous ores of the Temple Mountain district.

Hematite (Fe_2O_3) is mainly a cementing material in the detrital rocks, but it was recrystallized and, along with barite, locally added to sandstone near ore in the Delta mine.

SULFATES AND CARBONATES

Barite, calcite, and dolomite occur as primary gangue minerals in the ores. Barite ($BaSO_4$) is found in deposits on Green Vein Mesa and at the Wickiup claims and probably occurs in trace amounts in the interstices of the sandstones and in concretionary masses in most of the deposits in the Temple Mountain Member. At the Wickiup claims, barite lightly stained with dusty hematite is intergrown with dolomite, chalcopyrite, and chalcocite(?) in the interstitial spaces of coarse-grained sandstone. Barite also occurs in hematitized sandstone peripheral to ore at the Delta mine.

Calcite and dolomite are locally concentrated in or near ore and are assumed to have been introduced or recrystallized during the ore-forming process. In the Temple Mountain district, dolomite ($CaMg(CO_3)_2$) forms nodules and irregular roll-like masses near the ore. The ore itself is almost free of carbonates. Relations of ore to carbonates are less definite in most other deposits, but reconnaissance of many mines shows minor concentrations of carbonate nodules (mainly calcite) peripheral to ore.

SILICATES

The silicate minerals include one ore mineral (coffinite), the typical detrital minerals composing the bulk of the ore-bearing sandstone, and alteration products such as jasperoid, kaolinite and mica clay, and vanadium- or chromium-bearing silicates formed or recrystallized epigenetically.

Coffinite ($U(SiO_4)_{1-x}(OH_{4x})$) has been identified by X-ray methods by Abdel-Gawad and Kerr (1963, p. 32) from mineralized jasperoid in the Dirty Devil 6 mine and the Magor mine (near the Cistern deposit). It also occurs sparsely in the Temple Mountain district.

Chromium- or vanadium-bearing silicates are found principally in the Temple Mountain district, where they occur in ore or in altered zones adjacent to ore. Apparently they formed largely by alteration and by addition of vanadium and chromium to micas or clay minerals that were detrital constituents of the rocks.

Kaolinite is widely distributed in the sandstone and mudstone of the Monitor Butte, Temple Mountain, and Moss Back Members in the San Rafael Swell (Schultz, 1963), and, as such, it is probably partly of detrital or diagenetic origin. Part of the kaolinite, however, which is coarsely crystalline and which forms nodules and replaces detrital minerals, probably is of epigenetic origin, for it seemingly is more abundant in altered rocks.

Mica clays of probable illitic composition locally surround asphaltite nodules in the Temple Mountain district and are inferred to have formed at about the same time as the asphaltite. Abdel-Gawad and Kerr (1963, p. 40) have proposed that some mica clay in the lower part of the Chinle Formation has formed from montmorillonite during epigenetic alteration.

Jasperoid nearly identical with that found in the purple-white rocks is found locally in ore at the Dirty Devil 4 mine, Lucky Strike mine, and at other mines or prospects. The jasperoid contains anomalously high concentrations of barium, and it generally contains small amounts of asphaltite and sulfide minerals.

CARBONACEOUS MATERIALS

Coaly materials, petroleum, and petroleum derivatives occur in many rocks and are generally abundant in the uranium deposits. Most of the uranium in unoxidized ores, except in the Delta mine, is contained in a black lightweight (specific gravity generally less than 1.5) lustrous carbonaceous substance that has generally been called asphaltite.

The asphaltite occurs in nodules, interstitial fillings, massive aggregates apparently formed by replacement of sandstone and woody materials, and rarely in fracture fillings. In hand specimen it is distinguished by its physical properties and mode of occurrence; it is more lustrous than coaly material and harder than nonuraniferous asphaltites such as gilsonite. In polished section asphaltite is most easily recognized by its anisotropism and mottled appearance under crossed nicols.

Some asphaltites contain nearly 9 percent uranium (table 2), generally the most abundant metallic element in the asphaltite. Cobalt, copper, chromium, lead, nickel, zinc, vanadium, and other metallic elements also occur in the asphaltite; all these elements and the uranium are at least in part in separate mineral phases. Comparison of the analyses of asphaltite (or asphaltite ash) with the analyses of ores (table 4) suggests that the compositions of ore and asphaltite vary together. For example, molybdenum is not present in high concentrations in Temple Mountain ores, and it is not reported from Temple Mountain asphaltites; but, it is found in asphaltites from the southwestern part of the swell where molybdenum is present in relatively high concentrations in ore. The concentrations of copper, lead, vanadium, and zinc in asphaltites also appear to vary with the concentration of these elements in the ore.

Coalified wood or petroleum is found locally in nearly all of the rocks of the Chinle Formation, and mineralized coal and uraniferous

TABLE 2.—*Radiometric, chemical, and semiquantitative spectrographic analyses, in percent, of uraniferous asphaltite, San Rafael Swell*

[nd, not determined; leaders (----), not looked for; 0, not present or below threshold; M, major constituent, >10 percent. Analysts: C. G. Angelo (eU), D. L. Ferguson (U in ash, Ash), C. A. Horr (As and Se), C. S. Annell (spectrographic analyses), and J. S. Wahlberg and H. H. Lipp (V_2O_5)]

Laboratory No.	1	2	3	4	5	6
	AEC-8-21 253 455	NM-9-3 253 459	EM-4NE-1 253 457	DD-4-3 253 458	SRR-3F 253 456	RR-59L 232 025
Radiometric and chemical analyses of asphaltite						
eU	4.1	7.6	6.6	8.9	4.0	3.3
U in ash	5.69	7.96	7.86	8.83	4.53	4.34
V_2O_5	.94	10.56	<.05	<.05	<.05	.011
As	.1	.012	.170	.058	.140	nd
Se	.001	.0015	.0008	.0006	<.0001	.0002
Ash	19.19	26.53	27.54	30.12	16.66	nd
Semiquantitative spectrographic analyses of ash [1] of asphaltite						
Si	M	0.3	1.5	M	0.7	M
Al	3	.7	.7	1.5	.7	1.5
Fe	1.5	1.5	3	1.5	3	3
Mg	.15	.015	.07	.15	.07	.15
Mn	.03	.07	.07	.03	.03	.015
Ag	----	----	.0007	----	.0007	.0003
Be	.0015	.0007	.0003	.0015	.0003	.00015
Co	.07	----	.15	.03	----	.3
Cr	.015	.003	.003	.003	.003	.003
Cu	.007	.007	.15	.03	7	.7
Mo	0	0	.015	.07	.03	.007
Ni	.03	.015	.15	.03	----	.07
Pb	.3	.3	7	.7	.3	1.5
Y	.015	.007	.07	.03	.03	.03
Zn	.3	1.5	.3	.3	----	M
Zr	.03	.03	.03	.07	.03	.03

[1] Sample RR-59L was not ashed.

1. Massive replacement ore, Calyx 8 mine, Temple Mountain.
2. Asphaltite in veins in silicified wood, North Mesa 9, Temple Mountain.
3. Asphaltite associated with coalified wood, Eagle mine.
4. Small nodules and irregular replacement masses in layers of galena-rich sandstone, Dirty Devil 4 mine.
5. Nodules at sandstone-mudstone contact, Dexter 7 mine.
6. Nodules, Lucky Strike mine.

asphaltite are common in the ore deposits. In the Delta mine some high-grade ores are associated with logs that have nearly been completely replaced by uraninite. But at Temple Mountain the coalified wood is appreciably uraniferous only where it has been replaced by an asphaltlike substance. At some other places, such as the Lucky Strike mine, coaly materials are commonly mineralized, but asphaltite is also common.

SECONDARY MINERALS

Secondary minerals derived from the uranium-, vanadium-, copper-, molybdenum-, and cobalt-bearing ore minerals are present in the oxidized parts of the ore bodies. Besides the minerals that formed from relatively rare components of the ore, sulfates of common elements such as calcium and iron also are found in the oxidized part of ore bodies.

The secondary minerals are indicative of the trace-element content of the ore. They are also guides to ore, although not so useful in that respect now as they were in the earlier period of prospecting when the outcropping ore bodies were undeveloped. Secondary minerals, much like the primary minerals, are disseminated through sandstones, on bedding planes, and in carbonaceous materials, but joint control is much more important in secondary minerals than in primary minerals.

A considerable number of secondary uranium or vanadium minerals are found in the swell (table 3). The most common are carnotite (particularly at Temple Mountain), zippeitelike minerals, metazeunerite, and torbernite or metatorbernite. The rare minerals uvanite (Hess and Schaller, 1914), rauvite (Hess, 1925), abernathyite (Thompson and others, 1956), and rabbittite (Thompson and others, 1955), were first discovered at deposits in the San Rafael Swell.

In the swell, the secondary vanadium minerals pascoite, hewettite or metahewettite, and corvusite are apparently confined to the Temple Mountain district, although a copper-bearing vanadate, volborthite, has been reported from the Delta mine. Secondary copper minerals include malachite, azurite, antlerite (Hamilton, 1955), brochantite, and chalcanthite—all these are present at the Delta mine. Secondary cobalt and cobalt-iron minerals are locally abundant, particularly in the northern part of the swell and on Green Vein Mesa. Iron-bearing sulfates occurring abundantly at the Dexter 7 deposit on Calf Mesa include fibroferrite, copiapite, halotrichite, coquimbite, roemerite, siderotil, and diadochite (R. L. Akright, written commun., 1953). Gruner and Gardiner (1952) listed $(Co,Fe)SO_4 \cdot 6H_2O$ and $(Co,Fe)SO_4 \cdot 4H_2O$ from mines of the Green Vein Mesa area and $CoSO_4 \cdot 6H_2O$ from the Lucky Strike mine.

TABLE 3.—*Secondary uranium and vanadium minerals, San Rafael Swell, Utah*

[Compiled from Gruner and Gardiner (1952), Weeks and Thompson (1954), Keys (1954), Hamilton (1955), and Frondel (1958)]

Minerals	*Locality*
Uranium or uranium-vanadium minerals	
Oxides:	
Becquerelite ($7UO_3 \cdot 11H_2O$)	Lucky Strike, Consolidated, and Delta mines.
Schoepite ($4UO_3 \cdot 9H_2O$ or $2UO_3 \cdot 5H_2O$)	Consolidated and Delta mines.
Fourmarierite ($PbO \cdot 4UO_3 \cdot 7$ or $8H_2O$)	Lucky Strike and Delta mines.
Carbonates:	
Rutherfordine ($(UO_2)(CO_3)$)	Delta mine.
Bayleyite ($Mg_2(UO_2)(CO_3)_3 \cdot 18H_2O$)	Do.
Rabbittite ($Ca_3Mg_3(UO_2)_2(CO_3)_6(OH)_4 \cdot 18H_2O$)	Lucky Strike mine.
Schroeckingerite ($NaCa_3(UO_2)(CO_3)_3(SO_4)F \cdot 10H_2O$)	Delta mine.
Andersonite ($Na_2Ca(UO_2)(CO_3)_3 \cdot 6H_2O$)	Do.
Sulfates:	
Zippeitelike minerals (about $2UO_3 \cdot SO_3 \cdot nH_2O$)	Lucky Strike, Delta, Consolidated, Dexter, and Lone Tree mines.
Johannite ($Cu(UO_2)_2(SO_4)_2(OH)_2 \cdot 6H_2O$)	Consolidated mine, probably Delta mine.
Phosphates and arsenates:	
Autunite or meta-autunite ($Ca(UO_2)_2(PO_4)_2 \cdot 10–12H_2O$ or $Ca(UO_2)_2(PO_4)_2 \cdot 2\frac{1}{2}–8(?)H_2O$).	Wild Horse and Delta mines.
Torbernite or metatorbernite ($Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$ or $Cu(UO_2)_2(PO_4)_2 \cdot 4(?)–8H_2O$).	Temple Mountain district (small amounts of mineral); Hertz, Dirty Devil 6 (sparse minerals), and Delta mines.
Zeunerite or metazeunerite ($Cu(UO_2)_2(AsO_4)_2 \cdot 10–16H_2O$ or $Cu(UO_2)_2(AsO_4)_2 \cdot 8H_2O$).	Mines on Calf Mesa and Green Vein Mesa; Delta mine.
Bassetite ($Fe(UO_2)_2(PO_4)_2 \cdot 8H_2O$)	Possibly at Fuemrol (or Fumerol) mine, Temple Mountain district.
Abernathyite ($K_2(UO_2)_2(AsO_4)_2 \cdot 8H_2O$)	Fuemrol (or Fumerol) mine.
Phosphuranylite ($Ca(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$)	Wild Horse and Delta mines.
Vanadates:	
Carnotite and tyuyamunite or metatyuyamunite ($K_2(UO_2)_2(VO_4)_2 \cdot 1–3H_2O$ and $Ca(UO_2)_2(VO_4)_2 \cdot 5–8\frac{1}{2}H_2O$ or $Ca(UO_2)_2(VO_4)_2 \cdot 3–5H_2O$).	Temple Mountain district; minerals locally found at Delta mine and other localities.
Uvanite ($U_2V_6O_{21} \cdot 15H_2O$)	Temple Mountain.
Rauvite ($CaO \cdot 2UO_3 \cdot 5V_2O_5 \cdot 16H_2O(?)$)	Do.
Silicates: Uranophane or betauranophane ($Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$).	Delta mine.
Vanadium minerals	
Oxides: Corvusite ($V_2O_4 \cdot 6V_2O_5 \cdot nH_2O(?)$)	Temple Mountain district.
Vandates or related minerals:	
Hewettite or metahewettite ($CaV_6O_{16} \cdot 9H_2O$ or $CaV_6O_{16} \cdot 9H_2O(?)$)	Temple Mountain (in Wingate Sandstone).
Pascoite ($Ca_2V_6O_{17} \cdot 11H_2O$)	Temple Mountain district.
Volborthite ($Cu_3(VO_4)_2 \cdot 3H_2O$)	Delta mine.

The Delta mine has the greatest variety of secondary minerals, probably because of the variation in metal content within the deposit, and possibly because most of the uranium is in uraninite rather than asphaltite and thus is more easily broken down. The Delta ore body was locally rich in copper and vanadium, but vanadium was not everywhere abundant enough to fix uranium in the stable compounds carnotite or tyuyamunite (Weeks, 1956), so arsenates, phosphates, carbonates, oxides, and other minerals also formed. In many other mines asphaltite apparently protects the included finely divided uraninite from oxidation; the asphaltite also contains only a small fraction of the uranium contained in uraninite. Mines that had relatively abundant secondary uranium minerals during the early period of mining include the South Workings at Temple Mountain, the Lucky Strike mine, and, on Green Vein Mesa, the Consolidated mine.

METAL CONTENT AND CLASSIFICATION OF DEPOSITS

Although the ores in the San Rafael Swell are now valued for their uranium or uranium-vanadium content, the deposits locally contain copper, arsenic, zinc, or lead in amounts equal to or exceeding uranium or vanadium. They also contain other elements in concentrations that are at least of scientific interest.

Chemical, semiquantitative, and spectrographic analyses of ores and mineralized rocks show that various ores are enriched, relative to the barren sandstone of the Chinle Formation, in arsenic, copper, lead, zinc, cobalt, chromium, nickel, molybdenum, barium, strontium, and, rarely, lithium, rare-earth elements, and selenium, in addition to uranium and vanadium (tables 4 and 5). Copper and uranium locally exceed 1 percent, zinc and arsenic locally exceed 0.1 percent, and the other rarer elements are present in still smaller concentrations.

In terms of their enrichment relative to stratigraphically equivalent barren rocks (table 5), uranium and lead are the elements generally enriched by the largest amounts. Both elements are commonly enriched more than 100 times, and in some ores uranium is enriched more than 1,000 times. Arsenic, cobalt, copper, molybdenum, nickel, silver, vanadium, and zinc are generally enriched 10–100 times in deposits outside the Temple Mountain district. At Temple Mountain the same elements are enriched, but vanadium is strongly enriched (more than 100 times), as is selenium (more than 1,000 times); copper, molybdenum, silver, and zinc are generally enriched less than 10 times.

Some elements that were not detected in analyses of mill-pulp samples of the ore were detected in the spectrographic analyses of selected specimens. For example, cadmium and indium were detected from high-zinc specimens from the Lucky Strike and Dirty Devil mines. In the selected specimens, the zinc content ranges from 1.5 to more than 10 percent (as determined by semiquantitative spectrographic analyses), and the cadmium content ranges from 0.015 to 1.5 percent. Indium in trace amounts ($<$0.004 percent) was present in four samples. Thallium was not detected in any of the high-zinc samples, but its spectrographic sensitivity is relatively high (0.02 percent) and thus, even though expected, it might not be found.

Manganese, barium, and strontium are generally slightly enriched in deposits outside the Temple Mountain district. Barium and stron-

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TABLE 4.—*Composition (weight percent) of ore and mineralized rock, San Rafael Swell, exclusive of the Temple Mountain district*

Analyses 1–11 were used to calculate the average composition given in table 5. nd, not determined; M, major constituent, >10 percent; Tr., trace constituent. Chemical analyses by E. J. Fennelly, H. H. Lipp, Claude Huffman, and G. T. Burrow; spectrographic analyses by N. M. Conklin and J. C. Hamilton]

	1	2	3	4	5	6	7	8	9	10	11	12	13
Chemical analyses (unless otherwise noted)													
U	0.25	0.19	0.22	0.24	0.11	0.11	0.10	0.13	0.14	0.30	0.22	0.015	0.22
V	<.05	≈.035	.15	.12	.049	.035	<.035	.05	.11	.03	.03	[1].015	1.42
Se	.00006	.0015	<.00005	.00005	<.00013	<.00005	.0004	.0002	.00006	.00005	.0004	nd	nd
As	.028	.02	.032	.032	.063	.004	.0086	.03	.075	.003	.18	nd	[1].3

Spectrographic analyses (unless otherwise noted)

Si	M	M	M	M	M	M	M	M	M	M	M	M	M
Al	3	3	3	3	1.5	1.5	1.5	1.5	7	7	3	3	7
Fe	1.5	.7	1.5	.7	1.5	.7	1.5	1.5	.7	1.5	.7	1.5	.7
Mg	.3	.3	.3	.3	.3	3	3	.7	.07	.15	1.5	.3	.3
Ca	7	.7	.7	.3	1.5	7	3	1.5	1.5	.7	M	.07	.07
Na	.15	.15	.15	.15	.08	.07	.3	.15	.3	.15	.3	.07	.07
K	1.5	1.5	.7	1.5	.6	.7	3	3	1.5	1.5	3	≈.7	3
Ti	.15	.07	.15	.3	.08	.07	.15	.15	.15	.15	.15	.15	.3
Mn	.15	.015	.015	.007	.03	.15	.15	.03	.03	.03	.15	.015	.003
B	.003	.003	.003	.003	<.0015	0	.003	.0015	0	.0015	.003	.003	.007
Ba	.07	.03	.03	.07	.4	.015	.03	.07	.15	.7	.7	.07	.15
Sr	.015	.007	.015	.015	.011	.015	.03	.015	.03	.03	.03	.015	.015
Ag	0	.000015	.00015	.00015	.00005	Tr.	Tr.	.00003	.0003	.00015	0	~.00015	.0007
Ce	0	0	Tr.	Tr.	0	0	0	0	0	0	0	~.0003	.015
Co	.03	.015	.003	.003	.003	.0015	.007	.015	.003	.015	.015	.003	.015
Cr	.003	.003	.003	.003	.002	.0015	.003	.003	.0015	.0015	.003	.003	.007
Cu	[2].25	.015	.07	.07	.03	.07	.007	.07	.7	.7	[2].4	.07	1.5
Dy	0	0	0	0	0	0	0	0	0	0	0	~.0003	0
Ga	.00015	<.0002	Tr.	.00015	<.0003	<.0004	Tr.	<.0002	.0015	Tr.	Tr.	~.0007	.0007
La	0	0	.007	.007	Tr.	0	.003	0	.003	.003	.007	~.0007	.007
Li	0	0	0	0	0	0	0	0	0	0	0	~.0015	0
Mo	.003	.007	.007	.015	.002	.0015	.015	.003	.0015	.003	.0015	~.0007	.007
Nb	0	0	<.001	<.001	Tr.	<.001	0	0	<.001	<.001	0	.0015	.0015
Nd	0	0	<.01	<.01	Tr.	<.01	0	0	<.01	<.01	.015	~.00015	.015
Ni	.03	.007	.003	.003	.003	.0015	.003	.007	.003	.015	.015	.003	.03
Pb	[2].05	.07	.03	.03	.06	.03	[2].089	.03	.007	.03	.05	.003	.07
Y	.007	.003	.007	.003	.003	.0015	.003	.0015	.0015	.015	.015	.015	.03
Zn[3]	.18	.08	.05	.02	.18	.15	.08	.2	.08	.02	.075	~.00015	.07

[1] Spectrographic analyses. [2] Chemical analyses. [3] 1–11 are wet chemical analyses; 12 and 13, spectrographic.

1. Cistern mine, average composition (weighted geometric mean) of 3 samples representative of 600 tons.
2. Delta mine, composition of 1 sample representative of 85 tons.
3. Dirty Devil 1 mine, composition of 1 sample representative of 8 tons.
4. Dirty Devil 2 mine, composition of 1 sample representative of 10 tons.
5. Dirty Devil 3 and 4 mines, average composition (weighted geometric mean) of 3 samples representative of 210 tons.
6. Dirty Devil 6 mine, composition of 1 sample representative of 10 tons.
7. Conrad mine, average composition (weighted geometric mean) of 3 samples representative of 50 tons.
8. Lucky Strike mine, composition of 1 sample representative of 225 tons.
9. Consolidated 1 and 2 mines, average composition (weighted geometric mean) of 2 samples representative of 25 tons.
10. Green Vein 3 mine, composition of 1 sample representative of 8 tons.
11. Pay Day mine, composition of 1 sample representative of 15 tons.
12. Mineralized rock on West Castle Peak, representative of 8 chip samples from channels of Temple Mountain Member of Chinle Formation.
13. Uneva prospect, composition of 4-ft channel sample.

TABLE 5.—*Partial average composition (weight percent) of ore and unmineralized sandstone*

[nd, not determined]

	1	2	3
U	0.17	0.0002	0.19
V	<.053	.0022	.38
Se	<.00013	~.00002	.024
As	.024	~.001	.026
Mn	.042	.017	.013
B	≈.0015	~.001	nd
Ba	.092	.044	.036
Sr	~.017	.0082	.009
Ag	.00005	~.000003	.00001
Co	.0067	~.0002	.003
Cr	.0024	.0013	.017
Cu	.091	.0020	.008
Mo	.0037	<.0002	.0008
Ni	.0054	~.0003	.004
Pb	.037	~.0001	.007
Y	.0039	.0011	.002
Zn	.079	~.002	.017

1. Ore deposits, San Rafael Swell, exclusive of Temple Mountain district. These figures were compiled from analyses 1–11 in table 4.
2. Unmineralized sandstone from the Colorado Plateau. Analyses are from Newman (1962, table 12) and are based on 97 samples from the lower part of the Chinle Formation. Analyses of As, Se, Ag, Mo, Pb, Y, and Zn are from A. T. Miesch (written commun., 1961 and 1963) and are based on 30 samples from the Moss Back Member of the Chinle Formation.
3. Ore deposits, Temple Mountain district. Analyses from Hawley, Wyant, and Brooks (1965).

tium are also locally more strongly enriched in altered rocks outside the ore deposits than in the ore deposits themselves. Hematitized sandstone from the Monitor Butte Member near the Delta mine locally contains more than 10 percent barium, and jasperoid in purple-white altered rocks contains from about 0.03 to more than 10 percent barium and about 0.0015 to 0.3 percent strontium.

Inspection of the analyses (table 4) suggests that several of the elements correlate in a positive manner. Barium and copper, and, to some extent, cobalt and nickel appear to vary together. Molybdenum possibly varies with zinc or lead.

Mineralized rocks in the lower part of the Chinle Formation (represented by cols. 12 and 13, table 4) contain spectrographically measurable amounts of cerium, lanthanum, dysprosium, neodymium, and lithium. The yttrium content of these deposits is locally higher than in most of the ore deposits, but the concentrations of copper or of lead and zinc are similar. Although most of the occurrences of rare earths and lithium are in the Monitor Butte or Temple Mountain Member, some lithium and trace amounts of rare earths were detected in samples from the Moss Back Member at the Rock House prospect in the northern part of the swell.

CONTRASTING METAL CONTENT OF THE TEMPLE MOUNTAIN DEPOSITS

The metal content of the Temple Mountain deposits is different in several respects from the metal content of other deposits of the swell. Chromium, selenium, and vanadium are strongly enriched (more than 10 times) in the Temple Mountain ores but are only slightly enriched in most other deposits (table 5). In contrast silver and molybdenum are relatively sparse in most Temple Mountain ores, but are relatively abundant in several other deposits. Also barium, manganese, calcium, and magnesium, which are slightly enriched in most ore deposits of the swell, are not enriched in Temple Mountain ores and, in fact, are generally present in slightly less than background amounts.

CLASSIFICATION OF DEPOSITS

Deposits are classified, rather simply and objectively, by their metal content. They may be classified and described as vanadium-uranium, copper-uranium, or zinc-(lead)-uranium deposits, depending on their dominant and characteristic (in parentheses) metals. Some copper-rich uranium deposits contain measurable amounts of rare earths.

The vanadium-uranium deposits are mostly in the Temple Mountain district, and all known deposits in the Temple Mountain and Flat Top areas in both the Moss Back and Wingate are of this type. A few small deposits rich in vanadium are found outside the district; they are different from the Temple Mountain deposits in that they are sparsely seleniferous. Copper-uranium deposits occur at the Cistern mine and on Green Vein Mesa, and the zinc-(lead)-uranium deposits are at the Dirty Devil, Conrad, and Lucky Strike mines.

The copper-uranium deposits with slightly anomalous rare-earth content are mainly in mineralized rock; also small deposits occur in the Temple Mountain Member.

METAL ZONING

Metals are distributed zonally on several scales ranging in extent from hand specimen to a district or belt. Some of the zoning correlates with stratigraphic occurrence of ore but other zoning appears to be geographic. Stratigraphic zoning is suggested by the fact that copper-rich ores are in the Temple Mountain or Monitor Butte Member rather than in the Moss Back Member; at Temple Mountain, it is suggested by the fact that highly vanadiferous deposits are in the Wingate Sandstone and less vanadiferous but generally similar deposits are in the Moss Back.

Zonal distribution is suggested by local gradations between the copper-uranium and zinc-(lead)-uranium deposits. The ore body in the Delta mine was copper rich in the northern part and lead rich in the southern part, a fact suggesting a transition between types in one ore body (Keys, 1954). In other mines, such as the Lucky Strike, there is a vertical gradation from copper-rich ore near the base of the ore to relatively zinc-lead-rich ore in the upper parts. Deposits transitional from copper rich to zinc rich may be represented by the Cistern mine and by some of the copper-rich mines on Green Vein Mesa, which contain appreciable concentrations of zinc and lead.

Geographic zoning of metals in the Temple Mountain district is rather obvious and can be seen on several scales (Hawley and others, 1965). Vanadium and arsenic vary together in content and have a large-scale systematic distribution; they are most abundant in deposits on North Temple Mountain near the Temple Mountain collapse, and they decrease in abundance downdip and southward in the Temple Mountain mineral belt. On a smaller scale vanadium, selenium, cobalt, nickel, and chromium are enriched relative to uranium in zones outside ore bodies in Moss Back deposits, and chromium and possibly lead are enriched in zones outside ore bodies in the Wingate deposits.

ALTERATION AND ORE DEPOSITION

Besides the widely distributed altered rocks discussed earlier, small concentrations of altered rocks were formed in and near the ore deposits as part of the ore-formation process. The ore-related altered rocks are particularly abundant in the Temple Mountain district.

Ore-related alteration included (1) introduction and redistribution of carbonates, (2) partial removal of petroleum and its transformation into uraniferous asphaltite, (3) formation of jasperoid, and (4) formation of chromium- and vanadium-bearing silicates. The carbonatization and removal of petroleum can be noted both in deposits at Temple Mountain and in those elsewhere in the swell. Formation of jasperoid in and near ore was confined to deposits in the South and North mineral belts, whereas formation of metalliferous silicates took place mainly at Temple Mountain.

Of the four groups of regionally altered rocks discussed earlier only the purple-white altered rocks show a consistent relation to ore alteration. The regionally altered rocks of the Glen Canyon Group show a possible relation to mineralization at Temple Mountain, but the bleached Moenkopi Formation shows no apparent relation to mineralization. The bleaching of claystone and siltstone units below the Moss Back Member is not confined to regions of ore deposits, but the mudstones of the Moss Back generally show a slight anomalous metal content consistent with a regional ore-related alteration.

Silicification of ore-bearing host rocks was noted particularly at the Blue Bird prospect and at the Dirty Devil 4 and Lucky Strike mines.

At the Blue Bird prospect a small uranium deposit which contains jasperoid and chalcocite was mined from the altered basal sandstone of the Monitor Butte Member. In ore-grade material the jasperoid is red; as the grade of ore decreases the jasperoid changes to a pale brown. At the Dirty Devil 4 mine dark asphaltite-bearing jasperoid was mined in sheared strongly uraniferous mudstone at the base of the Moss Back Member; lighter colored jasperoid with associated pale sphalerite is found in a silty basal conglomerate of the Moss Back in the lower grade ore. Dark asphaltite-bearing jasperoid also occurs in the lower part of the Lucky Strike ore body. Jasperoid also composed part of the ore-grade purple-white zone mined at the Green Dragon 3 mine.

The occurrence of jasperoid in both ore and purple-white altered rocks is one of three main lines of evidence which suggest a relation of ore to purple-white alteration in the South and North mineral belts. The others are the fact that the channel structures in these belts may be productive where they are in a zone of purple-white alteration but not elsewhere (fig. 18), and the anomalous trace-element content of purple-white altered rocks.

Comparison of analyses of altered purple-white mudstone (table 6, col. 3) with nearly unaltered Chinle mudstone (table 6, cols. 1 and 2) suggests that the formation of zones of purple-white alteration involved marked general addition of boron, barium, and copper; slight general introduction of chromium, nickel, uranium, vanadium, and zirconium; and a possible loss of manganese. Other elements such as cobalt, scandium, and strontium either are about the same in unaltered and altered rocks or show variable trends. Newman (1962, p. 423–424) noted that altered mudstone of the uppermost Moenkopi and lowermost Chinle generally contains more rare earths (and uranium) than reddish-brown presumably unaltered mudstone of either formation.

Of the rock-forming elements, sodium and potassium are rather markedly less abundant in altered mudstone than in the approximately equivalent unaltered rock. This probably reflects the increased kaolinite content of the altered rock. Further comparison of the analyses (table 6, col. 2) suggests that the mudstone of the Shinarump and Moss Back Members may be regionally altered. In general, these mudstones contain more barium, chromium, nickel, vanadium, and uranium than unaltered Chinle mudstone (table 6, col. 1), but less of these elements than the purple-white altered rocks (table 6, col. 3).

The alteration of the Glen Canyon Group is continuous with the pervasive alteration of rocks of the uppermost Chinle and Glen Canyon Group in the Temple Mountain district, a fact suggesting that the alterations are related.

TABLE 6.—*Composition of unaltered and altered mudstone*

[M, major constituent, >10 percent]

	Largely unaltered mudstone		Altered mudstone
	1	2	3
Si	M	M	M
Al	8.2	8.8	>7.7
Fe	1.8	1.7	1.9
Mg	.64	.72	.38
Ca	.12	.17	.33
Na	.36	.43	.17
K	2.5	2.7	1.4
Ti	.29	.32	.32
Mn	.0081	.012	.0048
Ba	.0084	.015	.45
Sr	.0087	.011	.0087
B	.0048	.0048	.0130
Be	.00013	.00016	.00017
Co	.00067	.0011	≥.00066
Cr	.0051	.0058	.0064
Cu	.0032	.0032	.022
Ga	.001	.0013	.0019
Ni	.0015	.002	.0033
Pb	.0006	.001	[1].00076–.0011
Sc	.0017	.0017	.0016
V	.0064	.0083	.012
U	.0004	.0006	[2].0013
Y	.0024	.0026	.0037
Yb	.0003	.0003	≤.0005
Zr	.018	.015	.024

[1] Upper limit assumes 0 values are second value below spectrographic threshold; lower limit of 0 values is averaged as such.
[2] Chemical determinations on 5 samples.

1. From Chinle Formation, Colorado Plateau. Analyses (from Newman, 1962, p. 423, table 16) are based on 41 samples.
2. From Shinarump and Moss Back Members, Colorado Plateau. Analyses (from Newman, 1962, p. 423, table 16) are based on 15 samples.
3. From Moss Back and Monitor Butte Members of the Chinle Formation, San Rafael Swell. Analysts: H. H. Lipp, Claude Huffman, G. T. Burrows, Joseph Haffty, R. G. Havens, and H. L. Worthing. Samples SR-13B-56, -13C-56 are from near Green Dragon; SS-3NW-1C, -3NW-1D, from Dexter mine area; Adams-2A, -2B, -2C, from near Adams mine; and C6-6A, -6B, -6C, and C3-1A, -1B, and -1D, from Delta mine area. Samples SS-3NW-1C and -1D are purple and gray siltstone from the Moss Back Member of the Chinle Formation; others are purple-white rocks from the Monitor Butte Member of the Chinle Formation.

AGE AND ORIGIN OF THE DEPOSITS

A great amount of information regarding the uranium deposits of the Colorado Plateau has accumulated, but their exact age and mode of origin are still largely speculative. A consensus has been reached about certain aspects of the deposits—namely, most deposits formed after sedimentation and at least slight burial and the first or primary ore minerals were generally low-valent species such as uraninite and montroseite. It is generally agreed, also, that many ores formed by replacement or reaction with carbonaceous materials, by common replacement of cement and, more rarely, by replacement of detrital grains. Except in the immediate vicinity of collapse structures or of a few faults, there is little evidence of vertical movement of ore solutions, and therefore lateral movement through permeable units is commonly assumed.

AGE

Determination of the age of the deposits is still one of the main and most vexing problems because theoretically the absolute age of radioactive deposits can be obtained from ratios of the radioactive isotopes and their ultimate daughter products. The isotopic data on the Colorado Plateau ores are, however, ambiguous because the ages obtained from $U^{238}:Pb^{206}$, $U^{235}:Pb^{207}$ and $Pb^{207}:Pb^{206}$ ratios are generally different or discordant. Different approaches have been used to resolve the discordance, and markedly different ages have been postulated. Miller and Kulp (1963, table 6, and p. 627) suggested that age data could be resolved by assuming loss of radiogenic lead, particularly Pb^{206}, from the deposits and that, accordingly, the ore at Temple Mountain formed about 110 m.y. (million years) ago, or in mid-Cretaceous time, and some other ores in Triassic host rocks formed virtually syngenetically. Stieff, Stern, and Milkey (1953, p. 15), in contrast, assumed addition of an old radiogenic lead at the time of formation of the deposits, and they postulated that the ores most probably are of Late Cretaceous or younger age. They determined an age of 80 m.y. on asphaltic ore from the Camp Bird 13 mine in the Temple Mountain district. Later Stieff and Stern (1956, p. 554) and Stieff (1958, p. 302) showed that lead minerals deposited with the uranium contained anomalous amounts of radiogenic lead which probably did not form at the sites of the uranium deposits, evidence strengthening their assumption of addition of radiogenic lead during the formation of the deposits. Granger (1963) pointed out that Ra^{226} has migrated from uranium ore bodies in the Ambrosia Lake area, New Mexico, and that in effect this migration has resulted in $U^{238}:Pb^{206}$ ages that are too young. He believes that these deposits in the Morrison Formation are likely older than 100 m.y. In the face of these divergent opinions, we believe that the geologist must resort to relative dating by geologic criteria.

On direct evidence, the uranium deposits of the swell can be dated only as younger than collapse structures, bedding-plane fractures, and introduction of petroleum and as older than most high-angle faults. The relative dating of these events as summarized below seems most consistent with a Laramide age of mineralization.

Collapse structures in the Temple Mountain district and Reds Canyon–Sulphur Canyon area are locally mineralized and hence predate the ore. The collapses of the swell are associated with cross warps or subsidiary folds of the San Rafael anticline and probably are nearly contemporaneous with folding. Bedding-plane fractures could likewise be contemporaneous with folding, particularly as the associated low-angle fractures of the Temple Mountain district fall in a set whose strike parallels the fold crest and whose dip is consistent with movement during folding.

The deposits formed after petroleum was introduced. This line of evidence is also consistent with a Laramide age, but because petroleum was probably first introduced into the rocks along the old northwest-trending anticline, it conclusively shows only that the deposits are epigenetic. The relative age of petroleum to ore has been discussed extensively in the companion report on the Temple Mountain district (Hawley and others, 1965). Briefly, it is pointed out that ore bodies composed largely of uraniferous asphaltite grade, in one direction, into petroliferous rock. In the opposite direction the ore is in abrupt contact with porous altered rock containing only interstitial asphalt. The occurrence clearly implies that altering solutions were introduced into petroliferous rocks and that petroleum, largely displaced from the now-altered rocks, left only residual asphalt. The petroleum did not move far, but it was concentrated as asphaltite at the sharp ore-altered rock contact.

In the Temple Mountain district additional evidence favoring a Laramide age is found in the belt of deposits there, whose orientation is parallel to local structure and whose structural location is above the anticlinal bend of the San Rafael monocline. Further evidence is the alteration of the Glen Canyon Group. These rocks are regionally altered in the structurally higher parts of the San Rafael anticline, and they are altered more intensely and pervasively, as well as continuously, with regional alteration at Temple Mountain; therefore, their alteration could also have occurred about at the time of folding.

A further problem of the age of deposits is whether or not all uranium deposits in the swell are contemporaneous. Because of their similarities the deposits in a particular belt might reasonably be assumed to be nearly contemporaneous. It may not, however, be valid to assume that mineralization at Temple Mountain was contemporaneous with that in the North and South belts. In fact the Temple Mountain deposits are tentatively believed to be slightly younger than those of the rest of the swell because of (1) evidence of three periods of metallization recorded in the coals of the district, (2) anomalous metal content of some ores in the basal Moss Back at Temple Mountain, and (3) apparent superposition of Temple Mountain alteration on purple-white alteration. These criteria are discussed more fully by Hawley, Wyant, and Brooks (1965); all indicate some superposition of metallization in the district. The oldest metallization found in the district was probably diagenetic, and it is recorded mainly in the pyrite in cells and cell walls of coaly materials; second generations of pyrite and sphalerite were also deposited in the coals before the major uranium mineralization. This intermediate-aged metallization possibly coincides with the period of purple-white alteration, as suggested by the facts that purple-white alteration preceded the main period of alteration and mineralization at Temple Mountain and that jasperoid in the purple-white zone at Temple Mountain contains concentrations of pyrite and sphalerite.

ORIGIN OF DEPOSITS IN THE NORTH AND SOUTH BELTS—A HYPOTHETICAL TREATMENT

Several facts must be explained by any hypothesis generally applied to the Chinle uranium deposits. Two of these—the postdiagenetic age of the ore and its occurrence in discontinuous sandstone bodies near the base of the Chinle Formation—have been widely recognized. A third fact—that a mineralized sandstone body lies about at the stratigraphic position of a zone of sheared and altered rock—has not.

A hypothesis seemingly compatible with these observations is that the uranium deposits formed from hydrothermally contaminated formational waters that moved laterally through permeable zones at and near the contact of the Moenkopi and Chinle Formations. These zones are largely conformable with the sedimentary layering, but they are partly in mudstone and partly in sandstone or conglomerate lenses and were largely localized by bedding-plane fracturing. The permeability of parts of zones in sandstone is largely primary or intrinsic; the permeability of mudstone must be essentially secondary and takes place through bedding-plane and related fractures. Under this hypothesis the zones in mudstones are marked by shearing, by purple-white mottling, by presence of sparsely metalliferous jasperoid and carbonates, and locally by small ore bodies. In sandstone they are marked locally by jasperoid or carbonates and by ore deposits.

The hypothesis of movement of solutions through zones of partial secondary permeability at or near the Moenkopi-Chinle contact is consistent with vertical position of ore bodies in the belts. It also seems to explain some deposits, such as that of the Delta mine, that are difficult, if not impossible, to explain by lateral movement of solutions through zones of high primary permeability, because the deposit occurs in a sandstone lens apparently completely surrounded by mudstone.

An alternative place for widespread lateral movement of solutions is through the more continuous sandstone layers of the lower part of the formation, such as the Moss Back Member, and transmission of ore-bearing solutions through these units is widely accepted. It is, however, necessary to explain the sparsity of ore in the apparently more transmissive units. There is also the positive evidence, from purple-white alteration, that solutions did move laterally through the basal mudstone-rich rocks of the Chinle Formation.

Mudstone, though inherently less transmissive than sandstone, has certain features favorable to ore genesis. The montmorillonitic clays abundant in the Monitor Butte Member suggest the original presence of tuffaceous material which may have released uranium and other metals to formational waters during devitrification. Furthermore, the stability of hematite in the Monitor Butte versus the stability of pyrite in the Moss Back suggests that formational waters in mudstone-rich rocks were less reducing than were those of the sandstone and conglomerate bodies; so, ore metals might exist in soluble high-valent complexes that were stable as long as they were in their mudstone hosts. The relations between probable compositions of waters in sandstone and mudstone suggest a mechanism for the formation of the deposits: briefly, mingling of relatively oxidizing metal-bearing solutions contained in the mudstone with the more reducing water in sandstone would cause precipitation of metals as sulfides or reduced oxides in the sandstone.

The most likely sources of metals for the deposits seem to be formational waters or hydrothermal solutions derived ultimately from magmatic sources rather than the trace quantities of elements contained in the rocks themselves. This conclusion is based mainly on the anomalously high metal content of the altered rocks which suggests that metals were generally added during alteration rather than subtracted from the altered rocks and moved to the sites of the ore deposits.

Noble (1963) stressed the possible importance of formational water, particularly from compactible mudstone, as an ore-forming fluid. As pointed out above, formational waters from devitrifying tuffaceous rocks are likely to be abnormally uraniferous (provided the tuff had unusual uranium content) and thus are possibly ore-forming fluids. But the possible importance of such formational waters in actual ore genesis seems likely to vary with time of formation of the deposits, because most of the water of compaction is squeezed out with shallow burial of the formations. The relatively late origin of the deposits accepted as most likely here is not seemingly consistent with simple origin of deposits from formational waters. It is probably consistent with the expulsion of residual formational waters during the Laramide orogeny; and these solutions, after contamination by hydrothermal solutions, are proposed to be the ore-forming fluids.

The main evidence for contamination of the formational waters is not provided by the metals, whose source is difficult to assess, but by the apparent acidic character of the solutions which caused purple-white and ore-associated alteration. Aspects of the alteration which appear to be consistent with at least weakly acidic solutions are (1) displacement of Fe^{+3} in purple-white alteration, (2) redistribution of carbonates, and (3) argillic character of the alteration. Such alteration—as in either weathering or hydrolytic hydrothermal alteration—seems to indicate an excess of hydrogen ions which is not likely in uncontaminated formational water in tuffaceous sediments.

In summary, the bulk of the ores of the Chinle Formation probably can be explained by lateral migration of uraniferous fluids through nearly stratigraphic but structurally controlled zones near the basal Chinle contact, probably during the Laramide orogeny. It is obvious, on the basis of present data and the uncertainty of the age of the deposits, that other hypotheses could be constructed. If further studies of the altered zones indicate a diagenetic age rather than the epigenetic age assumed here, then it would be more reasonable to postulate the origin of many Chinle deposits from formational waters or, perhaps, a dual-stage mineralization involving early formation of the weakly mineralized purple-white rocks and later concentration of materials into the present ore zones.

ORIGIN OF DEPOSITS IN THE TEMPLE MOUNTAIN DISTRICT

The origin of the deposits in the Temple Mountain district is controversial and has been discussed extensively. Most earlier hypotheses are summarized in the companion report on that district (Hawley and others, 1965), in which it was proposed that the solutions responsible for the alteration and mineralization caused the collapse structures and that the collapses were the conduits for entry of solutions into the Moss Back Member and other mineralized strata. The ores of the district mainly formed as a reaction between introduced aqueous solutions and petroleum contained in the host rocks; and selenium, uranium, and arsenic among the introduced components very likely had sources distant from the deposits.

DESCRIPTIONS OF SELECTED MINES AND MINE AREAS

Uranium ore has been produced from more than 20 mines or mineralized areas in the San Rafael Swell, but mostly from the Delta mine and the Temple Mountain district. Deposits in the Temple Mountain district, South belt, and North belt are discussed. As the Temple Mountain district has already been described in detail (Hawley and others, 1965), it is only briefly discussed here.

TEMPLE MOUNTAIN DISTRICT

In the Temple Mountain district, which has an area of about 20 square miles, ore occurs principally in what is here called the Temple Mountain mine area; it also occurs in small- to medium-sized deposits at Flat Top in the western part of the district.

The district is underlain, in stratigraphic order, by the Moenkopi Formation, Chinle Formation, Wingate Sandstone, and the Kayenta Formation. Most of the uranium occurs in the Moss Back Member of the Chinle Formation. The Moss Back averages about 90 feet in thickness and overlies about 40 feet of mudstone and sandstone of the Temple Mountain and Monitor Butte Members of the Chinle. It is separated from the Wingate by the Church Rock Member which is composed mainly of mudstone and subordinately of sandstone and limestone pebble conglomerate.

The Moss Back Member of the area generally consists of a basal conglomerate or conglomeratic sandstone, in overlying massive sandstone, succeeded by a limestone-pebble conglomerate and an upper platy sandstone. Ore occurs locally in all four units, but it is most abundant in thick lenticular sandstone bodies of the massive sandstone unit. Sandstone of this unit is typically petroliferous and is less well cemented than the underlying and overlying units.

The rocks in the district generally strike north-northeast and have an average dip of about 9° SE. Locally, near the large composite Temple Mountain collapse, they dip as much as 40° toward the collapse.

Alteration is centered around the collapse structure and most notably affects the Church Rock Member of the Chinle Formation and the Wingate Sandstone. The Church Rock has been extensively bleached and locally altered to rock rich in siderite; the Wingate Sandstone and the rocks near the Church Rock—Wingate contact are locally dolomitized.

Large ore deposits in the Moss Back Member are found in the north-northeast-trending Temple Mountain belt extending from the Camp Bird 12 to the Vanadium King 1 workings. Smaller ore deposits occur updip from the belt on Temple Mountain. As suggested by outlines of the Temple Mountain mine workings, ore bodies in the belt trend generally northwest. Many are ore rolls elongate in the northwesterly direction.

The ore is mainly a carbonaceous mineraloid-asphaltite which contains uraninite and locally coffinite. Metallic minerals associated with the asphaltite include montroseite, pyrite, ferroselite, native arsenic, galena, and sphalerite. The ore is vanadiferous; $V_2O_5 : U_3O_8$ ratios in deposits in the Moss Back Member range from more than 4 on parts of Temple Mountain itself to about 2.3 to 3.8 in the main belt of deposits.

The ore also contains an average of 0.024 percent selenium, as contrasted with an average of <0.00013 percent in ore and mineralized rock from the rest of the swell.

SOUTH BELT

Uranium deposits are relatively numerous in a belt whose northern boundary trends northwestward across the swell from a point about 3 miles southeast of Temple Mountain on the east flank of the swell to the north end of Green Vein Mesa on the west. This belt, now largely eroded in the central swell, is termed the South belt (pl. 1).

The deposits occur mostly in scour-and-fill channels of the Moss Back Member, principally the Tomsich Butte channel (pl. 1), and in lens channels of the Monitor Butte Member. The deposits are discussed in four areal groups: (1) southeast flank, (2) Delta mine area, (3) southwest flank, and (4) Green Vein Mesa mine area. The data are most complete on the deposits in the Delta mine area and on those of the southwest flank of the swell.

SOUTHEAST FLANK

Along the southeast flank of the swell, deposits were examined only briefly, between Temple Mountain and the Delta mine; nevertheless, because of numerous small deposits and the medium-sized deposits of the Magor Mining Co., we believe that this area is particularly favorable for prospecting. Part of the area was described by Hinckley, Volgamore, and Potter (1955), and some aspects of the Magor mine have been described by Abdel-Gawad and Kerr (1963).

Along the outcrop belt ore is contained in the lower part of the Chinle Formation, either in sandstone or conglomerate lenses of the basal Monitor Butte Member or in scour-and-fill channels of the Moss Back Member. The Shinarump Conglomerate of Hinckley, Volgamore, and Potter (1955) is approximately equivalent to the combined Monitor Butte and Moss Back Members of this report. A small mineralized Moss Back channel is exposed near Chute Canyon (Little Erma mine), and a major Moss Back channel inferred to be the Tomsich Butte channel (Magor and Cistern mines) crops out west of Lower Wild Horse Point (pl. 1). (The Magor mine was developed after completion of our survey, but it is probably very close to the Cistern mine shown on pl. 1.)

DELTA MINE AREA

The Delta mine area is at the south end of the San Rafael Swell, where Muddy Creek flows out of the swell through a deep canyon cut principally in the Glen Canyon Group. The Delta mine, on the east side of Muddy Creek, is the largest single deposit yet found in the San Rafael Swell.

The area is underlain by the Moenkopi Formation, Chinle Formation, and Wingate Sandstone (pl. 3) of Triassic age and extensively mantled by colluvium and alluvium of Quaternary age. The sedimentary rocks strike about N. 70° E. and dip southeast. The Chinle Formation consists, in ascending order, of the Monitor Butte Member, 75–110 feet thick; the Moss Back Member, about 20–80 feet thick; and the Church Rock Member, about 150 feet thick. Uranium ore is apparently confined to lenticular sandstone bodies in the Monitor Butte Member. Specimen quantities of mineralized rock locally occur near the base of the Moss Back Member, in mudstone of the Monitor Butte, and in siltstone of the uppermost part of the Moenkopi Formation.

The Monitor Butte Member is mainly varicolored mudstone. Lenticular sandstone bodies are found locally at the base of the unit and in about the middle of the unit. The basal sandstone of the Monitor Butte, which forms lenses as much as 30 feet thick (pl. 3), is the Hunt sandstone of economic usage. A basal sandstone body was mineralized at the Blue Bird prospect on the west side of Muddy Creek. Medial sandstone lenses of the Monitor Butte are as much as 33 feet thick. One of them, the host lens for the Delta ore body, is as much as 800 feet wide and was originally more than 1,180 feet long, elongated in a northeasterly direction. The southwestern part of the lens has been eroded away.

The lens of Delta sandstone of economic usage, as shown by drilling and outcrop, was enclosed in mudstone of the Monitor Butte, although it did come within a very few feet of basal sandstone of the Monitor Butte in part of the mine (pl. 3). The mudstone which forms the bulk of the Monitor Butte Member is red, purple, or pale green. The mudstone lying between the basal and medial sandstones of the Monitor Butte is red, that at the stratigraphic position of the medial sandstone lenses is pale green, and that of the uppermost mudstone is purple. Both the pale-green and purple mudstones are altered rocks; they were probably red originally. The pale-green mudstones, laterally equivalent to the Delta sandstone of economic usage and to other medial sandstone lenses, locally are anomalously radioactive and contain copper minerals. Altered rocks are also found in the uppermost Moenkopi and locally in the basal Chinle Sandstone.

DELTA MINE

The Delta mine was discovered almost concurrently by prospector Vernon J. Pick and by geologists of the Atomic Energy Commission in June 1952. The ore body, which cropped out, was detected by the Atomic Energy Commission geologists using airborne scintillometers (Keys, 1954, p. 7). The discovery of this large ore body and the subsequent publicity on the mine greatly increased prospecting activity in both the swell and other parts of the Colorado Plateau. The mine was opened by Mr. Pick, but it was sold in 1954 to the Atlas Corp. and was operated by its sudsidiary, Hidden Splendor Mining Co., until 1957. The mine has produced more than 100,000 tons of ore. Mining of the remaining pillars began under different ownership in 1962. The mine was not studied in detail by the Geological Survey, and the following description is based mainly on maps and reports of U.S. Atomic Energy Commission geologists (Keys, 1954) and on informal discussions with these geologists and with John R. Mullen and Ray Schultze of the Hidden Splendor Mining Co. It is based partly on the detailed surface mapping (pl. 3) and reconnaissance of mine workings.

The mine workings (pl. 3) consist of a large room and pillar stope and long cross cuts driven eastward for exploration; 700 feet south of the mine is an exploration adit that trends slightly north of east for about 1,200 feet. The workings shown are complete to 1956, and additional mining has largely consisted of pulling pillars. Recent mining has involved stripping of the colluvium which overlies most of the mine workings.

The Delta ore body is mainly confined to a part of a large sandstone lens near the middle of the Monitor Butte Member, although locally the mudstone just below the sandstone lens was mineralized. It occupies only part of the medial sandstone lens exposed at the portal of the Delta mine. Minable ore, apparently nearly confined to the widest part of the sandstone lens, occupied a crudely circular area about 500 feet (north to south) by 400 feet (east to west) in size. The greatest thickness of the ore was about 20 feet, but generally only the basal third of the sandstone lens was strongly mineralized (Keys, 1954, p. 14). Relatively high grade ore with U_3O_8 content of more than 1 percent occurs in thin-bedded fine-grained micaceous sandstone near the top of the ore-bearing zone. Exploration drifts driven eastward continued in nearly barren sandstone for as much as 600 feet, where they entered laterally equivalent mudstone.

The ore consists of both oxidized and unoxidized ore minerals; uranium was mainly in uraninite, carnotite, and a zippeitelike mineral (Keys, 1954; Hamilton, 1955). Other uranium minerals listed by Keys are the oxidized minerals, metazeunerite, metatorbernite, beta-uranophane, schroeckingerite, andersonite, schoepite, rutherfordine, meta-autunite, becquerelite, phosphuranylite, and fourmarierite. The oxidized or high-valent uranium minerals were particularly abundant in the northern part of the ore body, where they were accompanied by abundant malachite and azurite. These copper minerals and associated copper-uranium minerals formed in part by the oxidation of chalcocite

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and covellite. Galena, sphalerite, pyrite, and bravoite accompany uraninite, particularly in the southern part of the mine.

The only primary or low-valent uranium mineral identified was uraninite; unlike most other mines in the San Rafael Swell, uraniferous asphaltite is sparse if present at all. The uraninite and accompanying sulfides occur as fine grains in disseminated ore in sandstone and as coarse masses where they have replaced fossil wood. Fossil logs in the central part of the ore zone have been almost completely replaced by uraninite, and they contained as much as 83.5 percent U_3O_8. A distinct mineralized aureole extended as much as 25 feet away from the logs (Keys, 1954, p. 19). The secondary uranium minerals were in part localized by joints and open bedding planes.

Keys (1954, p. 26) emphasized a zonal arrangement of minerals in the mine. North of the ore body the host sandstone is strongly hematitized and contains barite. The northern part of the ore body itself contained abundant copper and copper-uranium minerals. Although most of these minerals are of secondary origin, remnants of chalcocite and covellite indicate a high-copper primary ore in about the same place. In contrast, galena and relatively lead-rich ores were found in the southern part of the ore body. The occurrence of a zone of fracturing, alteration, and local mineralization laterally beyond the ore-bearing sandstone and the sparsity of mineralization in the overlying Moss Back Member and underlying basal sandstone of the Chinle suggest that the ore-bearing solutions moved laterally along bedding-plane fracture zones about at the stratigraphic position of the Delta sandstone of economic usage.

BLUE BIRD PROSPECT

The Blue Bird prospect, discovered about 1952 by Kay Hunt of Hanksville, Utah, is about 1,800 feet southwest of the Delta mine. It consists of an adit with about 280 feet of workings (fig. 19).

The prospect is in a sandstone lens at the base of the Monitor Butte Member; ore and mineralized rock occur in siltstone-pebble conglomeratic sandstone that forms the lower part of the lens. The basal sandstone at the mine is about 22 feet thick; the mineralized zone is about 8 feet thick. The siltstone pebbles in the mineralized unit were apparently derived from the underlying Moenkopi Formation.

Visible ore minerals are sparse. Chalcocite can be seen locally in the conglomeratic sandstone and in jasperoid that replaces siltstone. A grab sample of copper-bearing conglomeratic sandstone contained 0.13 percent copper and, by semiquantitative spectrographic analysis, 0.0015 percent silver, 0.15 percent arsenic, 0.07 percent barium, and 0.0015 percent lead. Thin layers of carnotitelike minerals coat small

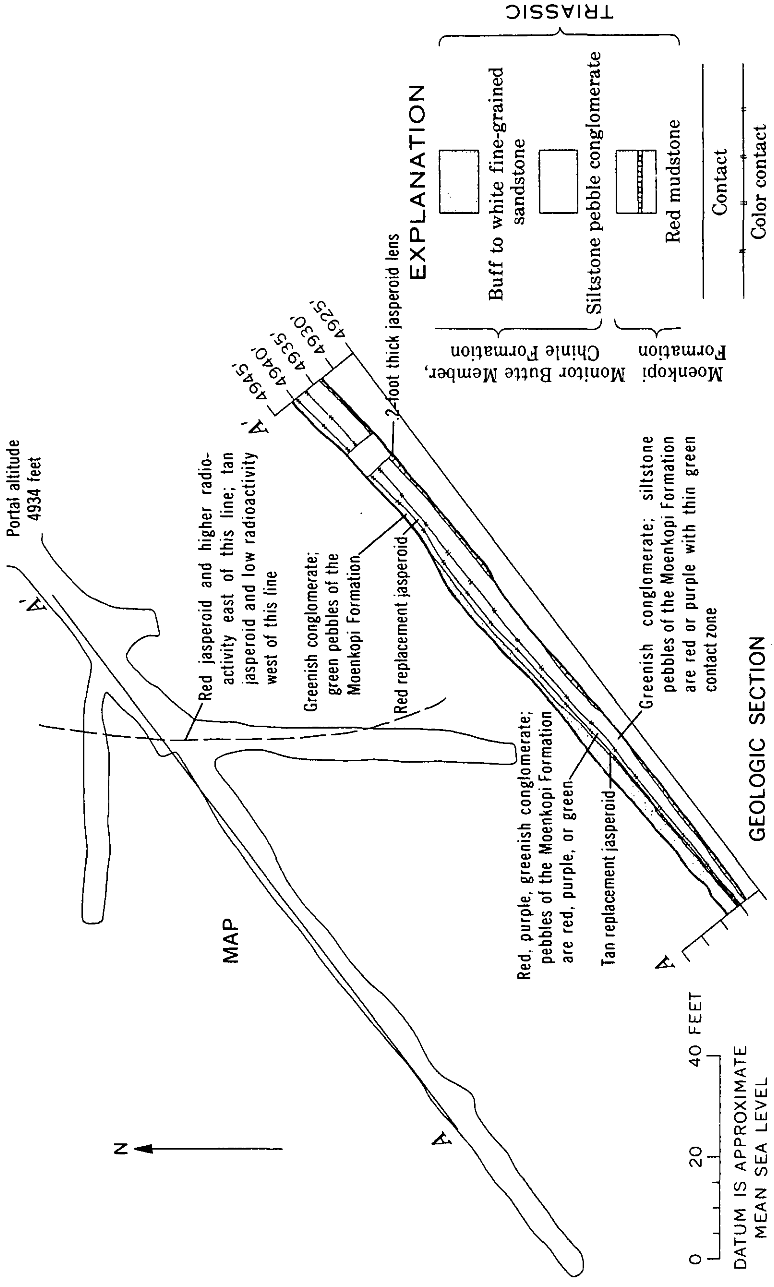

FIGURE 19.—Map and geologic section of the Blue Bird prospect.

patches on the outcrop, a condition probably indicating that small amounts of low-valent uranium and vanadium minerals are disseminated in the conglomeratic sandstone. Red jasperoid occurs in the part of the deposit where radioactivity is relatively high; tan jasperoid occurs in the conglomeratic sandstone where it shows low radioactivity (fig. 19).

Three color zones approximately parallel the bedding in the conglomeratic siltstone (fig. 19, section *A–A′*). The basal zone is green conglomerate which contains red or purple siltstone pebbles with pale-green borders; the middle zone is varicolored red, purple, and green with varicolored pebbles; and the upper zone is green with pale-green pebbles. The color boundaries locally cut across bedding, and the zones probably are alteration features caused by solutions moving laterally through the strata at the time of mineralization.

SOUTHWEST FLANK

Sedimentary rocks of Triassic and Jurassic age cut by thin, discontinuous igneous dikes of Tertiary(?) age are exposed along the southwest flank of the San Rafael Swell (pl. 4). The main ore-bearing unit, the Chinle Formation, is exposed in a rather narrow belt and on isolated buttes. It crops out on a steep slope with minor cliffs and local benches supported by sandstone-rich layers. Little if any Temple Mountain Member is present, and the formation consists of the Monitor Butte, Moss Back, and Church Rock Members. The Monitor Butte Member thins markedly northward: near the Delta mine the member averages more than 60 feet in thickness; south of the Lucky Strike mine it averages only about 40 feet, and near the Little Joe collapse structure it is probably about 30 feet. Locally the Monitor Butte is absent owing to channels of Moss Back.

Uranium occurrences are fairly numerous, and most are in scour channels of the Moss Back Member which were cut into the Monitor Butte Member or locally through it to the underlying Moenkopi Formation (pl. 1). The obvious channellike structures seen at the Dirty Devil, Conrad, and Lucky Strike mines probably are the result of local scouring and deposition within the major Tomsich Butte channel structure.

Near the Delta mine, the strata dip about 9° SSE. To the northwest along the Chinle outcrop belt, the strike of the rocks gradually swings northwestward, then northward and northeastward. Along most of the southwest flank of the San Rafael anticline the rocks dip 2°–5° W.

Faults of small vertical displacement cut the Chinle Formation about 2 miles northwest of the Delta mine, and larger faults cut the sedimentary beds near Tomsich Butte and Sulphur Canyon. Most of the faults belong to a set which strikes about west-northwest; a few strike east or northeast. A fault of the northeast set exposed east of Tomsich Butte is apparently displaced by faults of northwesterly strike.

Igneous dikes, which fill high-angle northwest-striking fractures, are found between Tomsich Butte and the Delta mine.

Three collapse structures—the South Reds Canyon, North Reds Canyon, and Little Joe structures—are exposed in the belt. Copper minerals, but no noticeably radioactive rocks, have been found at the South Reds Canyon collapse (see also collapse No. 8, Keys and White, 1956, p. 293). Both the North Reds Canyon and Little Joe collapse structures are locally uraniferous, and some uranium ore has been produced from the Little Joe structure.

The ore deposits exposed along the south flank contain visible sulfide minerals in addition to uraniferous asphaltite and, locally, uraninite. Galena and sphalerite are present megascopically in the Conrad and Dirty Devil mines, and galena is locally abundant at the Lucky Strike mine. Chalcocite(?) is present at the North Reds Canyon collapse, and molybdenite(?) at the Lucky Strike mine.

LITTLE SUSAN MINE AND RYAN 101 PROSPECT

The Little Susan mine and Ryan 101 prospect explore a northwest-trending channel in the Moss Back Member about 2 miles northwest of the Delta mine (pl. 1). The channel structure is shown by local thinning of the Monitor Butte Member (pl. 1)—to 30 feet at the Little Susan mine and to about 53 feet at the Ryan 101 prospect. In nearby areas the Monitor Butte Member averages about 60 feet in thickness.

The Little Susan mine consists of two connected adits having about 700 feet of workings including a small stoped area (pl. 5). The workings exposed the contact between the Monitor Butte and Moss Back Members. The Monitor Butte Member is dominantly mudstone, but it contains thin layers and lenses of sandstone. The basal part of the Moss Back exposed in the stoped workings (pl. 5) is a thin mudstone-conglomerate layer, which is overlain locally by a thin conglomeratic sandstone, which in turn is overlain by a thick layer or lens of cross-bedded locally petroliferous sandstone. Mudstone conglomerate and mudstone exposed at the contact are bleached and sheared. Shearing is particularly noticeable at the contact between mustone conglomerate and overlying sandstone or conglomeratic sandstone, and jasperoid and copper minerals are found along the shear zones. The sandstone or conglomeratic sandstone just above the bleached rock contains much introduced carbonate and only sparse petroleum.

Ore occurs in the basal Moss Back and in sandstone lenses of the uppermost Monitor Butte Member. The ore exposed in the walls of a small stope is mainly unoxidized, and it contains abundant pyrite or marcasite. At least part of the uranium is in small blebs of asphaltite disseminated in the sandstone. Copper and cobalt staining suggest the presence of sulfides that contained these elements in unoxidized ore.

The Ryan 101 prospect is about one-half mile northwest of the Little Susan mine and is inferred to be in the same sandstone-filled channel. It seems likely, however, that the channel has been largely eroded and that the relatively thick Moss Back exposed at the portal is the only remnant of a deep scour.

TOMSICH BUTTE AREA

In an area near Tomsich Butte are numerous uranium occurrences and several uranium ore bodies of as much as 4,000 tons. The larger ore bodies are in sandstone of the Moss Back Member that fills deep scours in the Tomsich Butte channel. Uranium minerals and at least one small ore body also occur in purple-white altered mudstone and associated sandstone in the lower part of the Chinle Formation.

The lower part of the Chinle Formation in the Tomsich Butte area is largely Monitor Butte Member. The member ranges in thickness from 0 in areas of deep filled scours of Moss Back to about 60 feet in Monitor Butte Member channels. It averages slightly more than 40 feet in thickness away from Moss Back Member channels, and it has a maximum thickness of about 60 feet near the Spanish Trails adit where a basal sandstone of the Monitor Butte Member fills a channel cut into the Moenkopi Formation (pl. 4).

The Moss Back Member ranges in thickness from about 36 to 120 feet. It is thin in the northeastern part of Dry Canyon and along the main outcrop belt about 1½ miles northeast of Tomsich Butte and is thickest on Tomsich Butte. The thin Moss Back Member contains red sandstone and siltstone interlayered with light-colored sandstone and is considered less favorable for uranium occurrences than the thicker generally lighter colored Moss Back. Lithologic units dominant in the ore-bearing scours are conglomerate and massive petroliferous sandstone.

Dirty Devil Group of Mines

The Dirty Devil mines are on Tomsich Butte in or near a major channel of the Moss Back Member. The most important mines are the combined Dirty Devil 3 and 4 mines on the south side of the Butte and the Dirty Devil 6 mine on the north side. The smaller Dirty Devil 1 and 2 mines are about one-fourth mile west of the Dirty Devil 3 and 4.

Ore was discovered on Tomsich Butte by W. J. Hannert and John

Tomsich in 1951, and considerable ore was produced from the Dirty Devil 3 and 4 and Dirty Devil 6 mines before 1956. The Dirty Devil 6 mine produced about 4,165 tons of ore to June 30, 1956, which averaged 0.185 percent U_3O_8 and about 0.05 percent V_2O_5. The combined Dirty Devil 3 and 4 mines produced about 4,096 tons that averaged about 0.197 percent U_3O_8 and 0.07 percent V_2O_5 during the same period. More recently a long exploration drift was driven northward from the Dirty Devil 4 mine, but only a small amount of ore has been produced from the new workings.

Ore cropped out at the Dirty Devil 6 mine, and the main ore body mined was a tabular body about 120 feet long and about 60 feet wide at the base of the Moss Back Member (fig. 20).

Ore at the Dirty Devil 3 and 4 mines was found principally in two well-defined ore bodies, which coincide in part with scours at the base of the Moss Back Member, and sparsely in less well defined ore zones (pl. 6). Although some ore cropped out at the Dirty Devil 4, the main ore body was reached about 240 feet north of the mine portal. Most uranium ore mined was from the basal Moss Back, but some high-grade material was mined in sheared mudstone of the Monitor Butte Member just below the contact.

LUCKY STRIKE MINE

The Lucky Strike mine is near the head of a side canyon that enters Reds Canyon about 5 miles northeast of Tomsich Butte (pl. 4). The ore body, which cropped out, was discovered about 1949, and by the end of 1957 it had produced more than 10,000 tons of ore averaging about 0.22 percent U_3O_8 and 0.09 percent V_2O_5.

The ore occurs in a scour filled with sandstone of the Moss Back Member and cut into the Monitor Butte Member (fig. 21). The mine workings consist mainly of a northeast trending stope, in part open to the east, and a crosscut driven northward, partly below the stoped workings (pl. 7).

The basal part of the Moss Back Member is composed of sandstone and chert-pebble conglomerate separated by thin mudstone splits. The richest part of the ore body was in a sandstone lens that interfingers with conglomerate to the north and probably to the south and west (pl. 7). High-grade ore occurred near coalified logs in the ore zone, but ore also occurs as bands of finely disseminated asphaltite and asphaltite nodules in sandstone away from woody material. Stratigraphically equivalent sandstone outside the ore zone is locally petroliferous. Ore also occurred sparsely in almost black jasperoid veins at the contact of the Monitor Butte and Moss Back Members.

Copper- and molybdenum-stained rocks found near the portal of the crosscut suggest concentration of copper and molybdenum in the

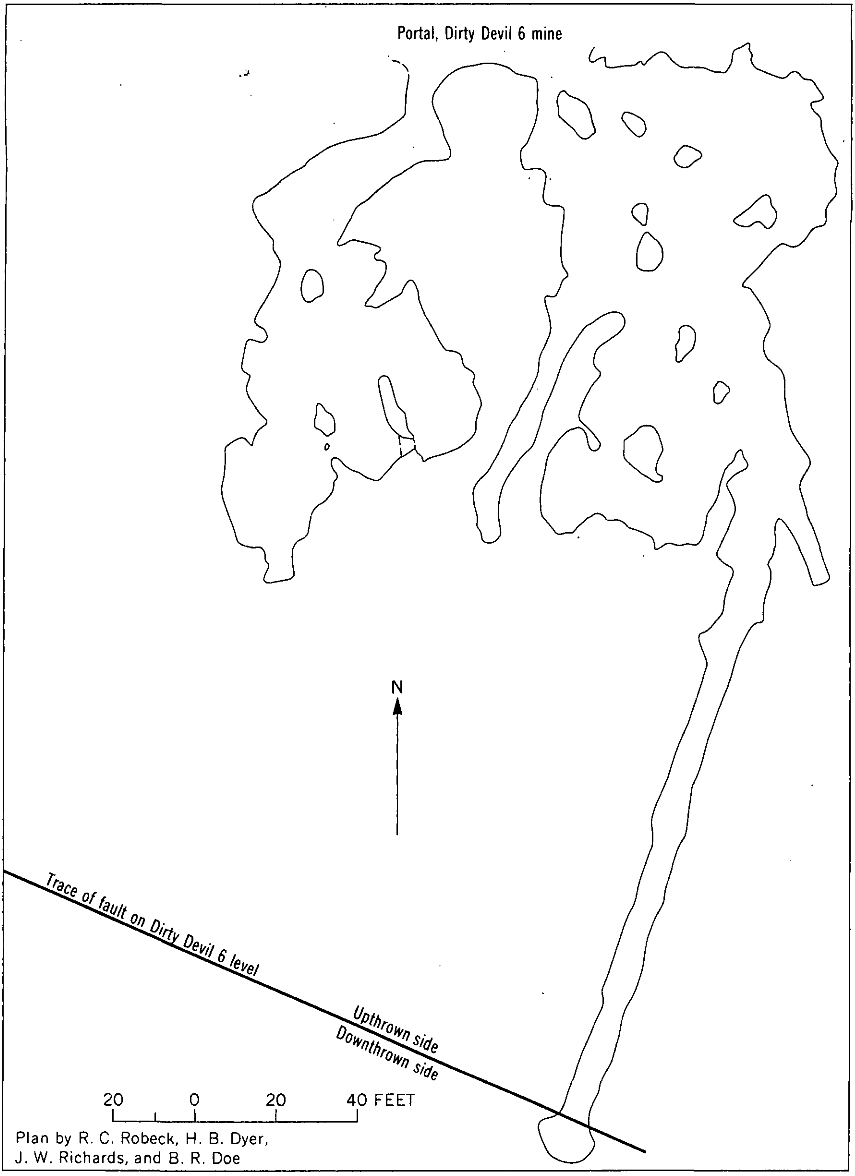

FIGURE 20.—Plan map of the Dirty Devil 6 mine.

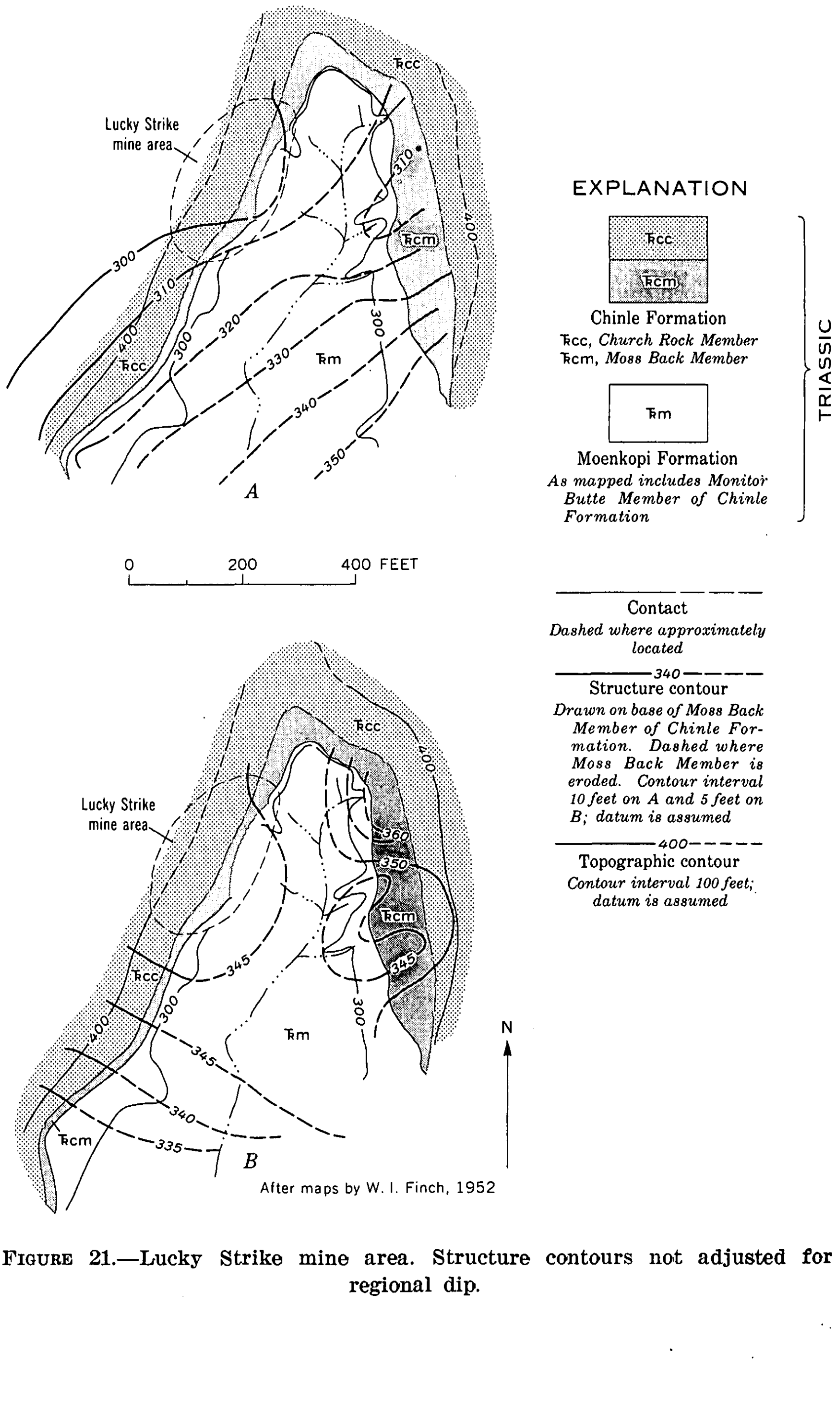

FIGURE 21.—Lucky Strike mine area. Structure contours not adjusted for regional dip.

lower part of the ore body. Galena was locally abundant in disseminated ore in sandstone.

GREEN VEIN MESA AREA

The Green Vein Mesa area includes the mesa itself and a large outlier called Family Butte. Copper and uranium minerals are widely distributed in the area and ore has been produced from several small mines (pl. 1) including the Consolidated, Dolly, Green Vein 2, 3, and 5, the Hertz, and Pay Day. More than 1,000 tons of ore was produced from the Consolidated mine through 1956 and more than 500 tons from the Hertz mine through 1955. All the deposits are chiefly at the contact of the Moenkopi Formation and the Monitor Butte Member of the Chinle Formation.

Results of reconnaissance investigations of the uranium deposits on Green Vein Mesa and on Calf Mesa in the northern swell area have been given by Reyner (1950) and Gott and Erickson (1952).

The Monitor Butte Member is sandier here than elsewhere in the South belt, a condition reflecting deposition in a north-trending channel structure of the Monitor Butte Member (pl. 1). In approximate order of abundance, the member is composed of argillaceous sandstone, greenish-gray mudstone, and limestone-pebble conglomerate.

A large high-angle east- to west-northwest-striking fault (pl. 2) cuts the rocks between Green Vein Mesa and Family Butte, and faults of the north-northeast set characteristic of the western part of the swell are exposed at several places. A north-northeast-striking fault exposed between the Pay Day and Green Vein 3 and 4 mines contains barite, which is also present in some of the ore deposits on the mesa.

PAY DAY MINE

The Pay Day mine is in a reentrant on the eastern side of Green Vein Mesa south of the Green Vein claims. The mine is developed by short connected adits (fig. 22) on the north side of the reentrant and a small prospect on the south side.

The mine is in the lower part of a locally carbonaceous limestone-pebble conglomerate. The host conglomerate is lenslike and probably fills a minor scour at the base of the Monitor Butte Member. At the mine portal the Monitor Butte is 30 feet thick; eastward, at the pinch-out of the conglomerate, it is only 18 feet thick.

Uranium occurs in small asphaltite nodules, in asphaltite(?) in replacement bodies in coalified wood, and in uraninite replacing the limestone-pebble conglomerate. The ore also contains copper sulfides, marcasite, jasperoid, and barite. The ore has a maximum thickness of about 3 feet, but it is generally much thinner and is concentrated in a zone at the Moenkopi-Chinle contact.

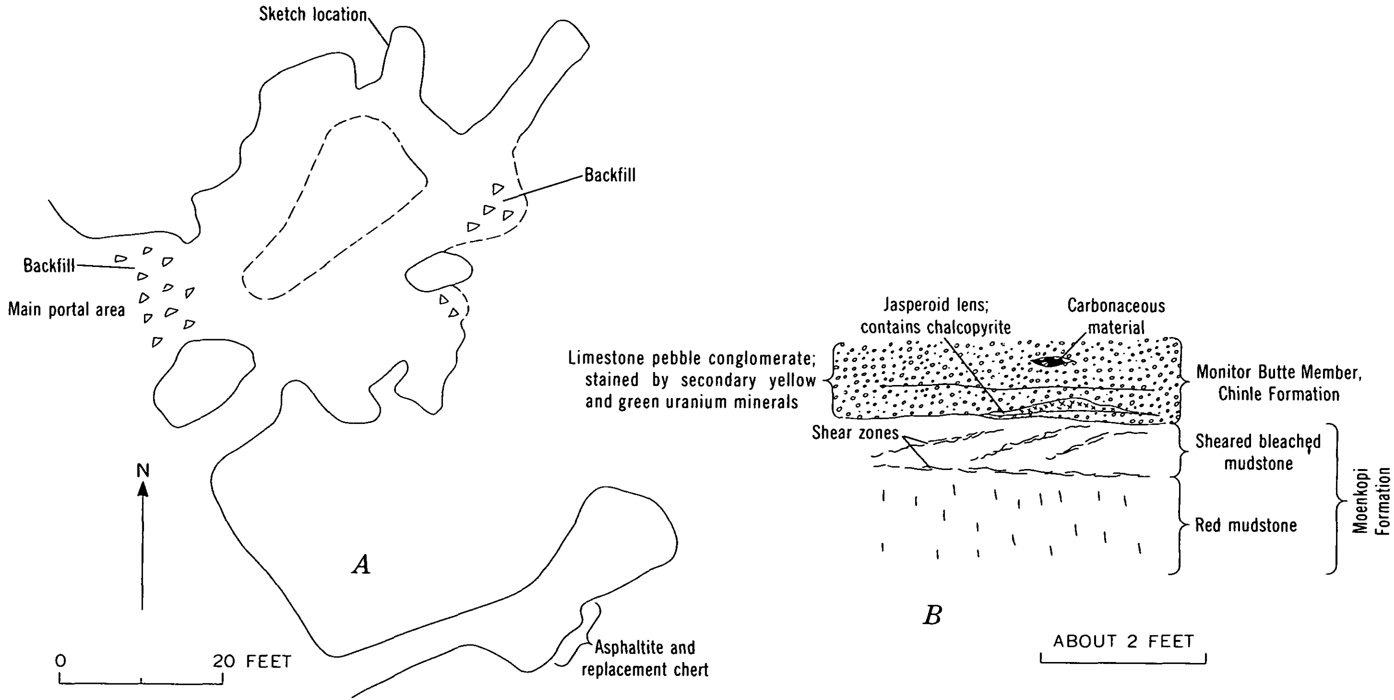

FIGURE 22.—The Pay Day mine. *A*, map. *B*, Sketch of sheared and altered rocks at the contact between Moenkopi and Chinle Formations. Mine map by P. H. Dobbs, R. W. Kopf, and R. L. White, U.S. Atomic Energy Commission, 1956.

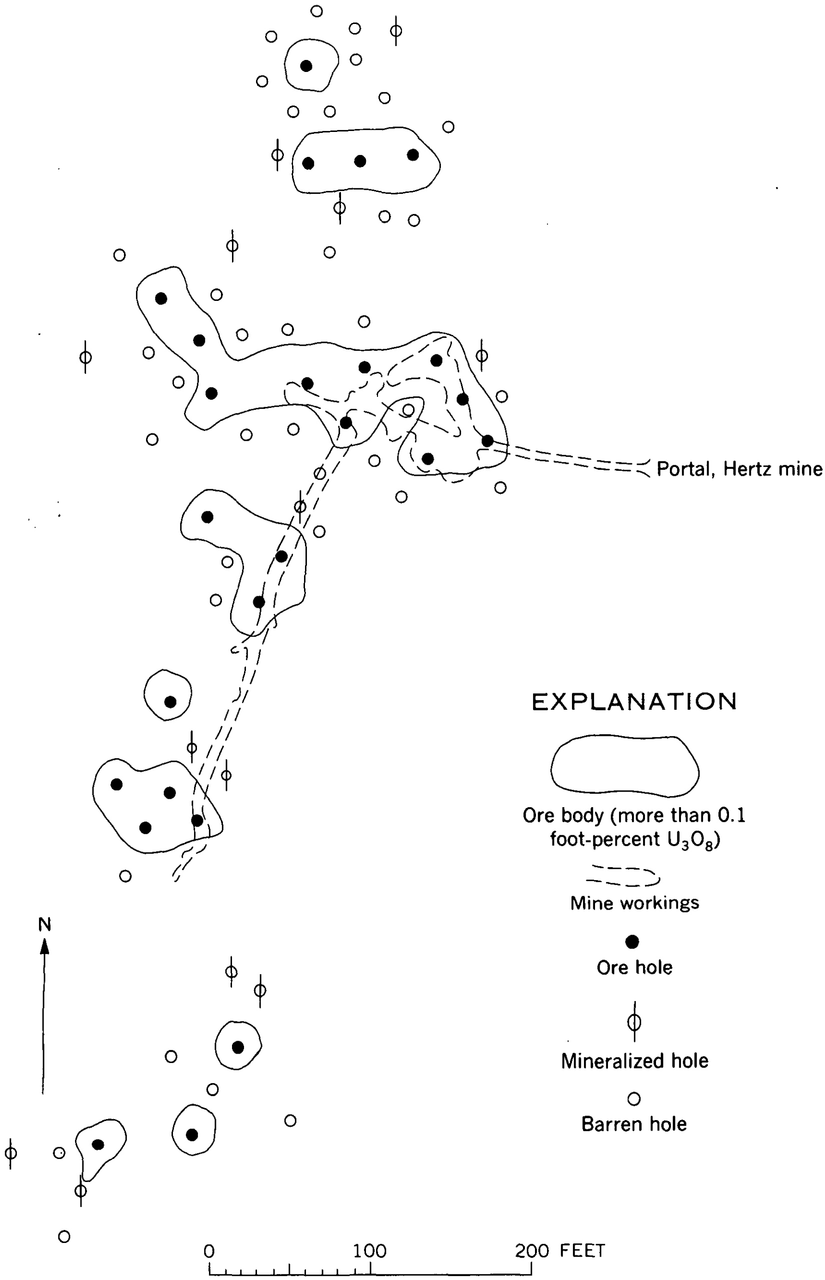

FIGURE 23.—Map of the Hertz mine showing results of drilling. Map by R. L. White, P. H. Dobbs, and R. W. Kopf, U.S. Atomic Energy Commission. Drilling information modified from R. D. Miller and K. J. Rogers (written commun., 1953).

HERTZ MINE

The Hertz mine is near the south end of Green Vein Mesa about 1,500 feet north of the Consolidated mine. Both mines seem to occupy scour areas in the same north-trending major channel structure (H. N. Jensen and R. K. Pitman, written commun., 1952; R. D. Miller and K. J. Rogers, written commun., 1953).

The ore occurs at and just above the base of a light-gray sandstone at the base of the Monitor Butte Member. Drilling data suggest that the ore forms small scattered bodies in a north-trending zone (fig. 23). The ore zones are generally thin but are locally minable because of the high grade of the ore, which locally exceeds 1 percent U_3O_8.

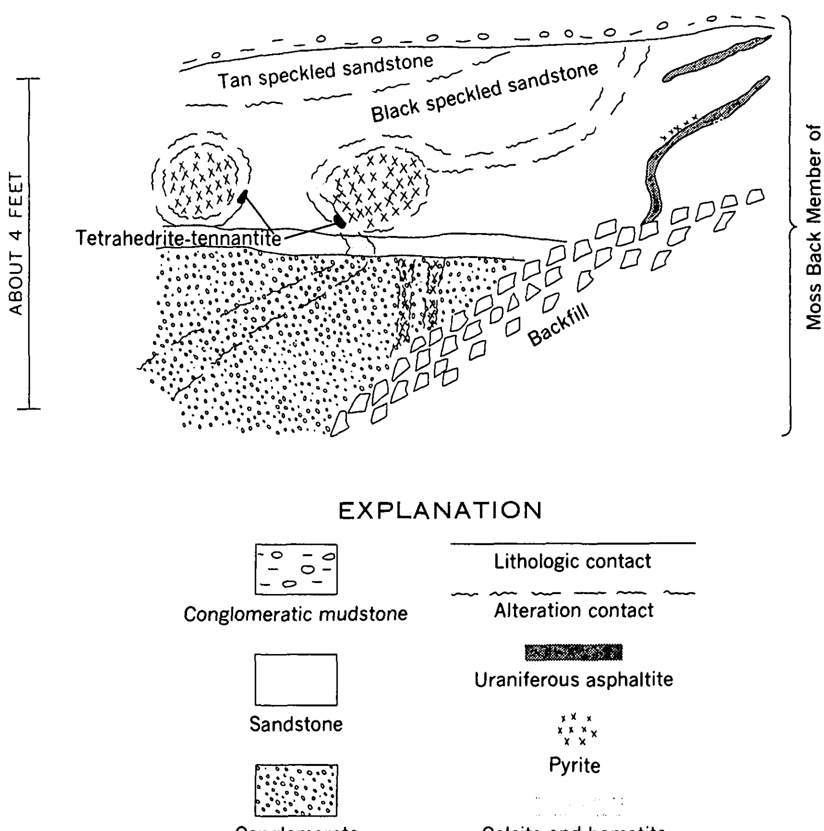

FIGURE 24.—Sketch of face in upper Dexter 7 adit.

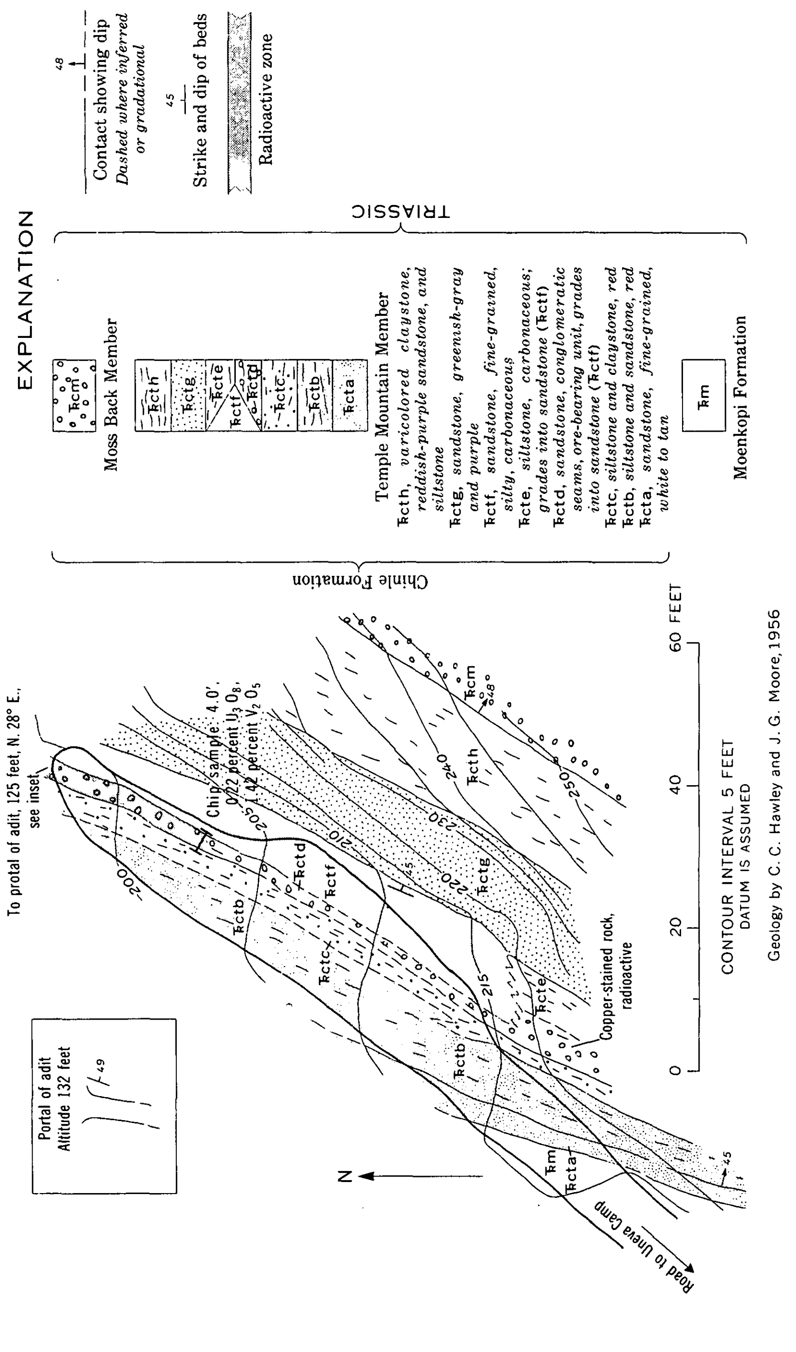

FIGURE 25.—Map of the Uneva prospect.

NORTH BELT

DEXTER 7 MINE

The Dexter 7 mine is near the south end of Calf Mesa in the northern part of the swell. From 1950 through 1957 the mine produced more than 500 tons of ore which averaged about 0.20 percent U_3O_8 and 0.05 percent V_2O_5. The mine workings consist of two short adits that were driven northwestward from near the base of the Moss Back Member and a third that was driven northwestward from a point about 30 feet above the base of the member. The Moss Back Member is abnormally thick in the area, and it fills channels cut into the upper part of the Temple Mountain Member.

Ore in the lower adits consists mainly of pods as much as 10 feet long of asphaltite ore lying subparallel to the bedding. In the upper adit ore occurs in nearly vertical pipes a few inches across and also in roll-like lenses which cut across the bedding (fig. 24). The rock adjacent to ore contains barren pyritic pipes. Zones of hematite-calcite rock are approximately parallel to the asphaltite ore zones and partly enclose barren pyrite masses. Copper minerals are locally abundant; primary copper minerals include chalcopyrite, tetrahedrite-tennantite, and probably chalcocite. Iron sulfate minerals are abundant at the portal of the southernmost lower adit (p. 73).

UNEVA PROSPECT

The Uneva prospect on the east flank of the swell is representative of uranium occurrences in the Temple Mountain Member in the North belt. Workings consist of a bulldozed cut and a short adit about 130 feet northeast of the cut (fig. 25). Ore occurs in a conglomeratic sandstone bed with sparse carbonaceous material about 12 feet above the base of the member. The beds strike north-northeast and dip about 45°–50° SE. The ore-bearing zone exposed near the north end of the cut is about 35 feet long and is as much as 4 feet thick. A 4-foot-thick sample contained 0.22 percent U_3O_8 and 1.42 percent V_2O_5.

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270-401 O - 68 - 8

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INDEX

[Italic page numbers indicate major references]

U.S. GOVERNMENT PRINTING OFFICE: 1968 O—270-401