Geology and Uranium Deposits of the Temple Mountain District Emery County, Utah

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GEOLOGICAL SURVEY BULLETIN 1192

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

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

Library of Congress catalog-card No. GS 65–310.

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

CONTENTS

Uranium deposits—Continued

ILLUSTRATIONS

[Plates are in pocket]

TABLES

GEOLOGY AND URANIUM DEPOSITS OF THE TEMPLE MOUNTAIN DISTRICT, EMERY COUNTY, UTAH

By C. C. Hawley, D. G. Wyant, and D. B. Brooks

ABSTRACT

The Temple Mountain district, Emery County, Utah, is on the southeast flank of the San Rafael Swell, one of the major topographic and geologic features of the western part of the Colorado Plateau. Some of the oldest mines in the plateau are in this district, which is one of the few where plateau-type uranium ores are associated with collapse structures and faults and with highly altered rocks.

The rocks cropping out in the district are sedimentary and range from Permian to Jurassic in age. With the exception of two thin marine limestones, the Kaibab Limestone and the Sinbad Limestone Member of the Moenkopi Formation, they are clastic rocks that were deposited on land or very near shorelines. The limestones and coarser grained rocks of all clastic units are locally petroliferous.

The oldest rocks exposed are light-colored generally fine grained sandstones of the uppermost 80 feet of the Coconino Sandstone of Permian age. These rocks are overlain by another Permian formation, the Kaibab Limestone, which averages about 25 feet in thickness but is locally thin or absent. The Moenkopi Formation, about 600 feet of Lower and Middle (?) Triassic rocks, disconformably overlies the Kaibab, and it, in turn, is unconformably overlain by the Chinle Formation of Late Triassic age. The Chinle Formation is divided into four members; the lower two, the Temple Mountain and Monitor Butte Members, are mapped as one unit that averages about 25 feet in thickness. The Temple Mountain and Monitor Butte Members are overlain disconformably by the Moss Back Member, 60–130 feet thick, which grades upward into the Church Rock Member, about 245 feet thick. The Temple Mountain, Monitor Butte, and Church Rock Members are mainly composed of fine-grained red and purple rocks, but the intervening Moss Back Member is mainly light-colored sandstone and conglomerate. The Moss Back is the main ore-bearing unit of the district and was deposited by a great generally northwest trending river system.

The cliff-forming Glen Canyon Group overlies the Chinle and forms the massive San Rafael Reef, which bounds the San Rafael Swell. The group totals about 1,200 feet in thickness and consists of the Wingate Sandstone of Late Triassic age, the Kayenta Formation of Late Triassic (?) age, and the Navajo Formation of Triassic (?) and Jurassic age. The youngest exposed rocks are siltstones and thin limy beds in the lower part of the Carmel Formation of Middle and Late Jurassic age.

The rocks generally strike about N. 55° E. and dip southeast—away from the axis of the northeast-trending San Rafael anticline. Eastward across the district the amount of dip increases gradually from a minimum of about 2° to

about 10° near the main outcrop belt of the Chinle Formation; there the dips steepen southeastward in a monoclinal flexure whose axis is parallel to the regional strike. Farther east the dip flattens to 9° or less. The generally homoclinal structure of the district is locally distorted by high-angle normal faults, northwest-trending crossfolds, and collapse structures.

The collapse structures (or collapses) are downwarped or downfaulted masses of altered rocks that are roughly oval shaped in plan. The largest of the five collapses exposed in the district is at Temple Mountain. East-west it is about 3,000 feet long, and it comprises rocks of at least the Moenkopi, Chinle, and Wingate Formations. The Temple Mountain collapse possibly is a composite structure formed from two or more main collapse elements arranged along one of the synclinal crossfolds of the district.

The collapses probably formed at least in part as the result of collapse or sag of younger rocks into voids formed by the solution of carbonate and possibly siliceous rocks. They are believed to have formed at about the same time as the folding of the San Rafael anticline.

Most of the uranium deposits of the district are unoxidized and are composed chiefly of a uraniferous carbonaceous mineraloid termed "asphaltite." The largest deposits are in the Moss Back Member of the Chinle Formation, but near the Temple Mountain and other collapse structures small uranium deposits occur in other rock units and in the collapse structures themselves. Most of the ore bodies can be classed as either rolls or tabular bodies. Most of the ore produced has come from deposits in the Temple Mountain mineral belt, a northeast-trending zone about 9,000 feet long. Ore bodies in the belt generally are oriented northwest and are as much as 700 feet long and 15 feet thick.

The distribution of ore was probably controlled by several factors, among which are collapse structures, the monoclinal upwarp underlying the San Rafael Reef, and paleochannels in the Moss Back Member. On a smaller scale the distribution of ore was controlled by mudstone splits, the shape of sandstone lenses, and, locally, fractures.

In comparison with equivalent barren rocks, the ores are greatly enriched in selenium, arsenic, and lead in addition to the principal ore elements uranium and vanadium. Iron and other rarer elements such as copper, chromium, and zinc are enriched to a lesser degree. In terms of weight percent, iron, vanadium, uranium, selenium, arsenic, chromium, and zinc are relatively abundant constituents of the ore.

The unoxidized ores contain, in addition to asphaltite, small amounts of pyrite, montroseite, sphalerite, uraninite, ferroselite, and, less commonly, other metallic minerals. Pyrite is the most common sulfide; it has several modes of occurrence and is found in the Moss Back Member in ores and in both uraniferous and nonuraniferous coals. Uraninite occurs as relatively coarse irregular grains and possibly as very fine round blebs in the asphaltite. Some of the uranium in the asphaltite is either in submicroscopic uraninite or in an organic complex. The gangue consists chiefly of the detrital grains of the host sandstones but includes some dolomite, clay minerals, and chromium-bearing mica clays that formed as alteration products. Petroleum is widespread in barren, unaltered host sandstones; a residual interstitial asphalt is common in altered sandstones near ore-bearing zones.

Asphaltite and closely associated ore minerals were deposited relatively late in the paragenetic history of the rocks; they formed after the hardening of the coals that are contained in the deposits. Some of the pyrite, sphalerite, and possibly other metallic minerals formed earlier, before the hardening of the

coals. Although most of the asphaltite formed after the deposition of the closely associated metallic minerals, the association suggests that asphaltite and closely associated minerals formed about contemporaneously.

At Temple Mountain, ore deposits in the Moss Back Member are generally richer in vanadium and arsenic nearer the collapse structure than farther from it. Selenium is most strongly enriched in the ore deposits of the Temple Mountain mineral belt at a median distance from the collapse. The distribution of other elements tends to parallel that of either vanadium and arsenic or selenium but in general is more complex. In individual ore bodies, chromium, selenium, vanadium, and a few other elements are distributed asymmetrically across roll or other sharp ore-body contacts.

Many of the rocks of the district are altered, and the effects of alteration are especially noticeable on Temple Mountain and near the other collapse structures. Solutions removed calcite and petroleum and formed clay minerals, dolomite, and siderite in the rocks near ore deposits or collapse structures. Both the color and composition of the mudstones in and near ore were changed during alteration.

The ore and associated alteration products, such as dolomite and chromium-bearing mica clays, may have formed about concurrently from carbon dioxide-bearing aqueous solutions that were introduced into the Moss Back Member and other strata through the collapse structures. The asphaltite was derived mainly from petroleum that was displaced by the introduced solutions; it was deposited near stabilized interfaces that formed between the introduced solutions and the petroleum contained in the rocks. These interfaces are now marked by sharp ore contacts.

Some of the metals found in the ore deposits, such as uranium, selenium, and arsenic, probably had their source at a considerable distance from the ore deposits; others, such as chromium and vanadium, may have been partly derived from nearby wallrocks during alteration. Some components of the introduced solutions, such as carbon dioxide, may have had an igneous origin.

INTRODUCTION

The prominent appearance of Temple Mountain, which rises above the Reef (the eastern boundary of the San Rafael Swell) and is clearly visible across the desert for many miles, undoubtedly attracted the attention of many travelers during the late 1800's. The discoverer and date of discovery of the Temple Mountain ore deposits are not recorded, but claims were staked in the district at least as early as 1898. Mining for uranium, vanadium, or radium began in 1914 and continued intermittently into the 1920's. After some 25 years of inactivity the mines were reopened, and they have been operated almost continuously since 1948. The district was one of the major uranium producers on the Colorado Plateau in the late 1940's and early 1950's.

The deposits at Temple Mountain are similar in form, metal content, and lithologic relations to many other deposits in the Colorado Plateau, but they differ markedly from most by their close association with altered rocks and collapse structures (or collapses) and by their occurrence in several widely separated stratigraphic units. In addition, they differ by detail of metal content, form, and stratigraphic position from most of the rest of the uranium deposits in the San Rafael Swell. Perhaps the major controversies in the rather imposing amount of geologic literature on the district concern the relation of the ores to the collapses and the genesis of the carbonaceous mineraloid, commonly termed "asphaltite," that is the chief metalliferous component of the ores.

Two main hypotheses have been proposed to explain the occurrence of ore deposits in several strata and the association of ore deposits with collapse structures. According to one hypothesis, the collapses are younger than bedded deposits of the Chinle Formation, and solutions, introduced through the collapses, leached uranium and vanadium from the deposits in the Chinle and redeposited them in other formations. The second hypothesis proposes that the collapses predate the uranium deposits and are the channels through which uranium-bearing fluids were introduced into the various strata. The results of our work support the second hypothesis. In addition to the collapse structures, other factors that contributed to the shape, size, and distribution of the ore deposits include folds, composition and structure of the sedimentary rocks, and the presence of petroleum in the rocks at the time of mineralization. The deposits thus reflect an interplay of geologic controls of several kinds. Our work also supports a petroliferous origin for the uraniferous asphaltite. The primary bases for this conclusion are in the apparent gradation of petroleum and the asphaltite and in the relations of petroleum and asphaltite to altered zones that contain only small amounts of interstitial residual(?) asphalt.

We consider that in addition to the knowledge it provides of the geologic history of the Temple Mountain district, the principal contributions of this study are an understanding of the following: (1) The relation of uranium deposits to the stratigraphy of the Moss Back Member of the Chinle Formation; (2) the relation of deposits and altered rocks to the collapses and other tectonic features; (3) the relations of altered rocks and ore deposits; (4) the zonal distribution of elements both within the deposits and, on a larger scale, around the Temple Mountain collapse.

GEOGRAPHY

The Temple Mountain district is in Emery County, Utah, approximately 45 miles southwest of the town of Green River, Utah, in Tps. 24 and 25 S., Rs. 11 and 12 E. (fig. 1), within the northwest part of the Temple Mountain 15-minute quadrangle. It is on the southeast flank of the San Rafael Swell, an elliptically shaped topographic and structural dome. The district can be reached by a paved road leading west from Temple Mountain Junction, on Utah Highway 24.

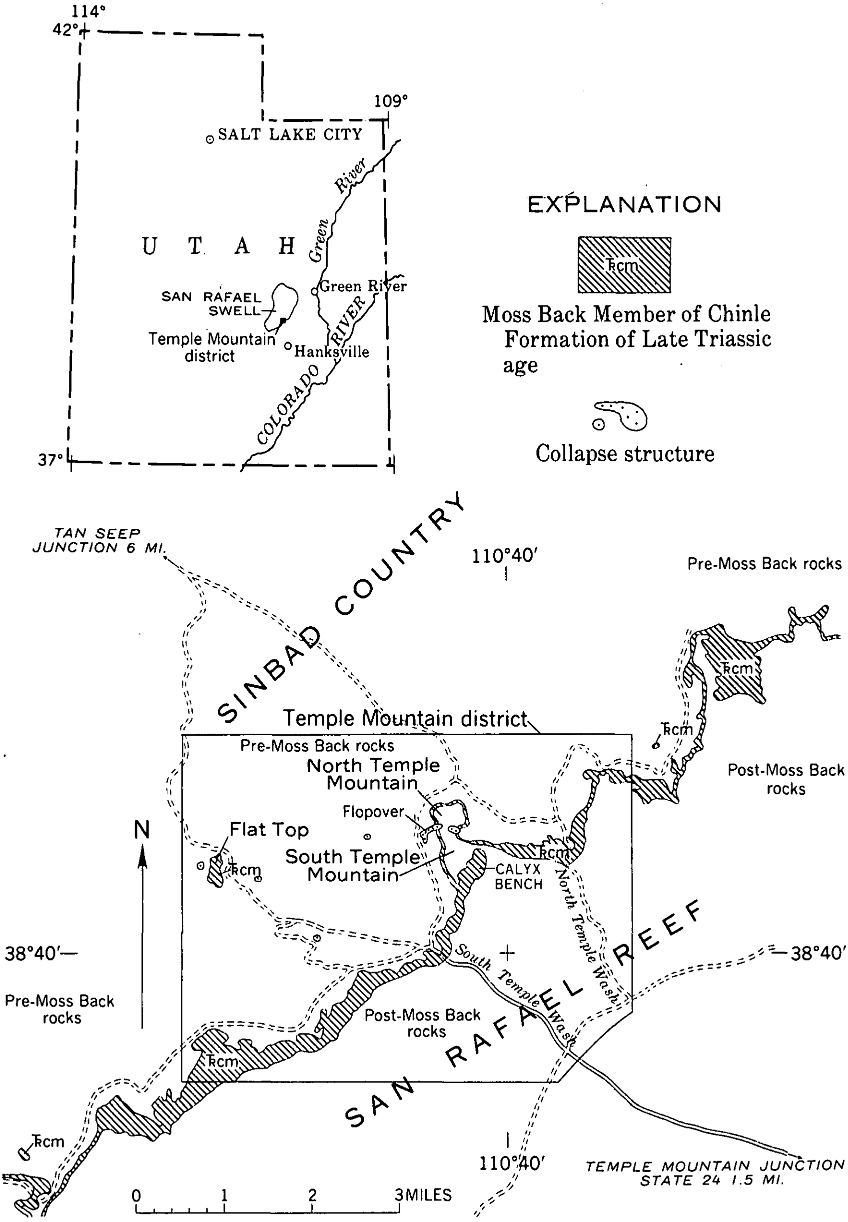

FIGURE 1.—The Temple Mountain district.

The district, as defined in this report, is a rectangular area of about 20 square miles that extends west across the great cliff, the San Rafael Reef, on the east flank of the San Rafael Swell onto the dissected inner part that is locally referred to as Sinbad or as Sinbad Country. The most conspicuous topographic feature is Temple Mountain, an erosional remnant of Triassic rocks rising nearly 1,000 feet above the surrounding terrain. A prominent mesa in the western part of the district is known as Flat Top (formerly Shinarump Mesa).

Temple Mountain is composed of two peaks—North and South Temple Mountains—separated by a saddle (fig. 2). Extending southwest from the saddle is an elongate mass of altered and collapsed rocks, locally known as the Flopover or the Tongue. The Flopover is part of the large composite Temple Mountain collapse. East and southeast of South Temple Mountain is a topographic bench—locally called the Calyx Bench—under which are the largest ore deposits in the district.

HISTORY OF MINING OPERATIONS AND PRODUCTION

Mining claims were staked in the Temple Mountain district as early as 1898 (R. C. Robeck, written commun., 1956), but no significant quantity of ore was produced until 1914 (Hess, 1916, p. 944). Between 1914 and 1920 a "considerable" but unknown tonnage of ore which averaged about 1.75 percent U_3O_8 and 4.0 percent V_2O_5 was shipped (Hess, 1933, p. 457). According to Coffin (1954, p. 6–7), the Temple Mountain deposits were the only deposits in rocks of Triassic age that contributed to the early production of radium on the Colorado Plateau. Between 1920 and 1948 only a small amount of ore was produced—"perhaps 150 tons or as much as 15 carloads" (F. M. Murphy, written commun., 1944). Extensive mining and production began in 1948 and accelerated owing to the development of processes enabling profitable extraction of uranium and vanadium from the asphaltic ores.

From 1948 through 1956 the district produced about 261,000 tons of uranium ore that contained about 1,287,000 pounds of U_3O_8 and 3,799,000 pounds of V_2O_5. Most of this ore came from an area near Temple Mountain (fig. 3); a small amount came from Flat Top in the western part of the district. During this period the Calyx 8 mine was the largest producer, contributing about 42,000 tons of ore containing 228,320 pounds of U_3O_8 and 753,809 pounds of V_2O_5. Other large mines were the Calyx 3 and Vanadium King 1.

The history of mining operations, even since 1948, is complex. Before 1948 most of the mining was done by the Standard Uranium Co.; between 1947 and 1951 several operators were active in the district. In 1951 all claims except those in the Vanadium King group were leased by the Consolidated Uranium Co., and from 1951 through 1956 Consolidated was the chief producer in the district. In November 1956, the interests of Consolidated were sold to Union Carbide Nu-

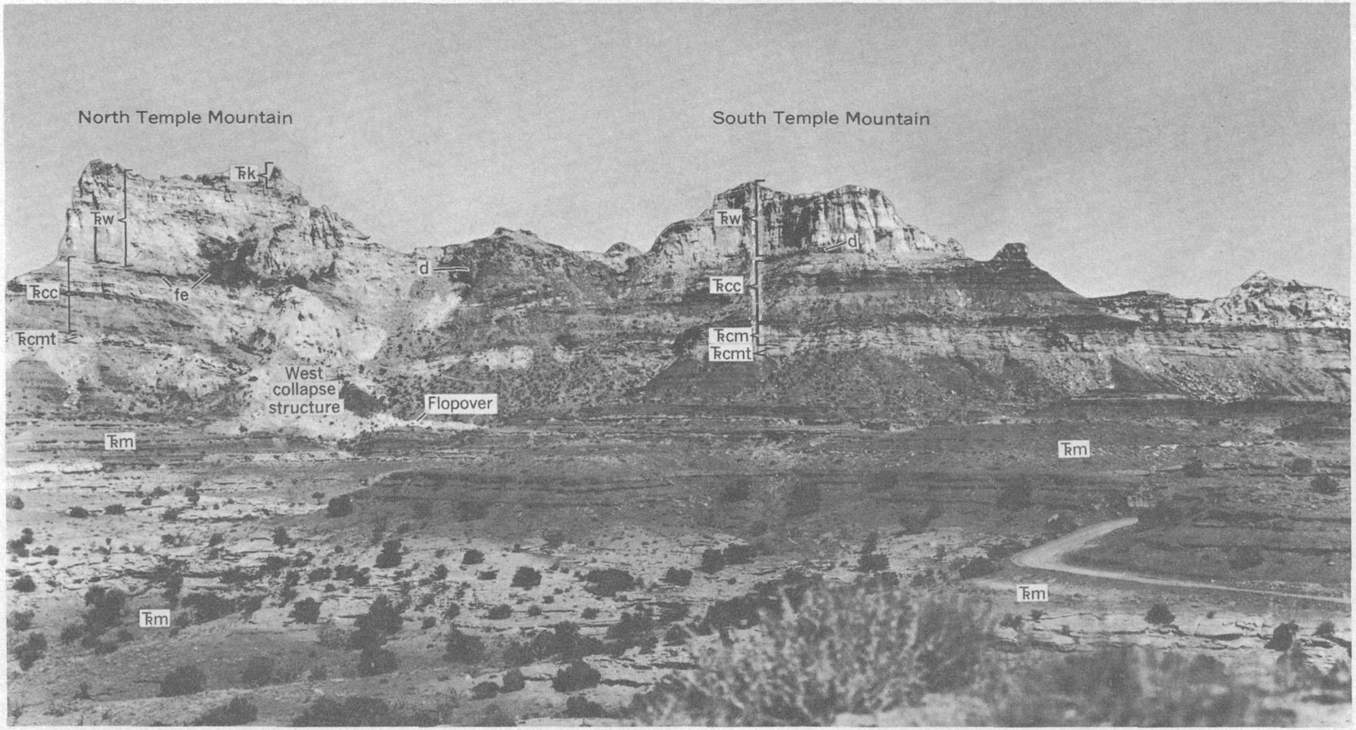

FIGURE 2.—Temple Mountain; view from the west. Ꞧk, Kayenta Formation (on North Temple Mountain only); Ꞧw, Wingate Sandstone. Members of the Chinle Formation are: Ꞧcc, Church Rock Member; Ꞧcm, Moss Back Member; and Ꞧcmt, Monitor Butte and Temple Mountain Members. Ꞧm, Moenkopi Formation. The Wingate Sandstone and Church Rock Member are altered to dolomitic (d) and ferruginous (fe) rocks near the collapse structure and in a zone near the Wingate–Church Rock contact.

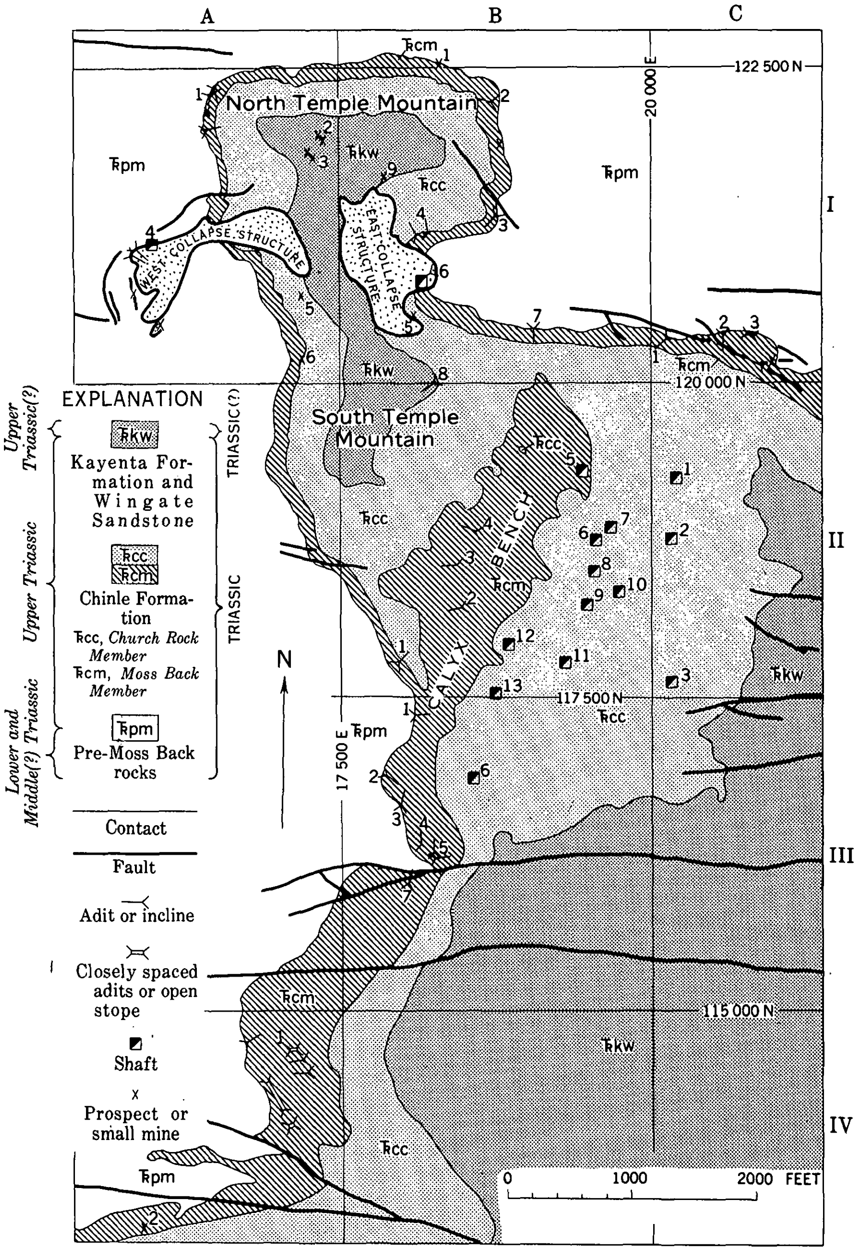

FIGURE 3.—Location of mines in the Temple Mountain area.

Mine names (by coordinates) shown in figure 3

AI-1	Camp Bird 7 (Wright workings)		
2	Eagles Nest		
3	Migliaccio prospect		
4	Fumerol		
5	Young prospect		
6	Unknown		
AIV-1	Camp Bird 12 group ("South workings")—Mountain King and Mountain King 1, 2, and 3 claims		
2	Black Beauty		
BI-1	Vanadium King 7		
2	4		
3	6		
4	5		
5	Unknown		
BI-6	Unknown		
7	Unknown		
8	Vagabond (Denny prospect)		
9	Unknown		
BII-1	North Mesa 10		
2	Marchbank incline		
3	Flewelling incline		
4	Baker incline		
5	Calyx (AEC) 6		
6	5¼		
7	5		
8	4		
9	10		
10	9		
11	3		
12	2		
13	2½		
BIII-1	North Mesa 9 (Camp Bird 14)		
2	7		
3	5		"Middle workings"
4	2	Camp Bird 13	
5	1		
6	Calyx (AEC) 1		
7	Lopez incline		
CI-1	Vanadium King 3		
2	1, portal 2	Rex mine ("North workings")	
3	1, portal 1		
CII-1	Calyx (AEC) 8		
2	11		
3	12		

clear Corp., and most of the recent production has been by Union Carbide or its lessees.

Most of the production since 1948 has been from new mines. The ore bodies under the Calyx Bench, largely discovered and partly blocked out by U.S. Atomic Energy Commission drilling in 1951 and 1952 (A. H. Anderson and R. D. Miller, written commun., 1952), have yielded over half the total amount of ore produced from the district. Minor production has been from the older mines, including the Camp Bird 12 group, North Mesa group, and the mines of the Vanadium King group, or from their dumps.

PREVIOUS GEOLOGIC WORK

The Temple Mountain district was a subject of geologic interest as early as 1913, and its economic geology has been reported on in varying detail since 1922. The recent interest in the geology of the uranium-vanadium deposits began in 1944 with the study conducted for the Manhattan Engineer District by the Union Mines Development Corp. The geologic literature on the area is probably as extensive as that on any uranium-producing area on the Colorado Plateau.

The areal geology of most of the east flank of the San Rafael Swell, including the Temple Mountain district, was mapped by Baker (1946); his report and those of Gilluly (1929) and of Hunt, Averitt, and Miller (1953) on other parts of the San Rafael Swell are the basic references on the general geologic setting of the district. The stratigraphic nomenclature of the main ore-bearing unit, the Chinle Formation, has been revised since these reports were written. The revisions, based on recent detailed stratigraphic studies by the U.S. Geological Survey, are reported in papers by Stewart and Smith (1954), Stewart (1957), and Robeck (1956).

The economic geology of the district was first studied by F. L. Hess of the U.S. Geological Survey. Hess first visited the district in 1913, and his reports of 1922 and 1933 are still valuable references on the mineralogy, mode of occurrence, and hypotheses of origin of the ores. He recognized the occurrence of uranium, vanadium, selenium, sulfur, and arsenic in the ores and the unoxidized nature of the asphaltic ore, and he discovered the secondary minerals uvanite and rauvite at Temple Mountain (Hess and Schaller, 1914; Hess, 1925). From Hess' report, the occurrence of ore in rolls evidently was well known to the early miners (oral commun. by R. H. Sayre, mine supt., cited by Hess, 1933, p. 456).

The area was studied in 1944 by geologists of the Union Mines Development Corp. (F. M. Murphy, written commun., 1944). Detailed geologic and topographic maps were made of the district, the outlines of mine workings were plotted, and the rocks of the mine workings and collapse structures were sampled. B. N. Webber, then of the Union Mines Development Corp. (written commun., 1944, 1947), strongly advocated a hydrothermal origin for the Temple Mountain ores, although he accepted a syngenetic origin for most other ores of the Colorado Plateau. In 1945, C. W. Chesterman and F. H. Main of the U.S. Geological Survey (written commun., 1947) visited the district, sampled the ores, and confirmed Murphy's estimate of the district's large uranium potential.

In 1946, W. L. Stokes, formerly of the U.S. Geological Survey, assisted by Wyant, measured 45 stratigraphic sections of the Moss Back Member of the Chinle Formation (the Moss Back Member was then called the Shinarump Conglomerate). The sections were spaced at approximately 1,000-foot intervals along 9 miles of outcrop northeast and southwest from Temple Mountain. Stokes observed a fourfold lithologic division of the Moss Back Member and the dominant northwest trend of the sedimentary structures in the Moss Back (written commun., 1946). Both observations were confirmed by detailed mapping by Wyant in 1947.

I. J. Witkind, R. C. Robeck, W. R. Barton, and G. A. Izett began an investigation of the district for the U.S. Geological Survey in 1953, and this work was continued by Robeck and H. B. Dyer in 1954–55 (written commun., 1954, 1956). This work contributed to the redefinition of the Chinle Formation. H. L. Cannon and R. L. Stillman of the U.S. Geological Survey (written commun., 1952) made geobotanical investigations and noted the concentration, on and near ore, of *Astragalus preussi arctus*—a selenium-indicating plant.

From 1951 through 1956 the district was studied by geologists of the U.S. Atomic Energy Commission, whose resident party was based at the Sinbad field camp. A report by Keys and White (1956) is an excellent account of the collapse structures and associated ore deposits. The results of other recent work on collapse structures, alteration, and genesis of the Temple Mountain deposits by geologists of the Atomic Energy Commission are given in several reports by Kerr and associates. (See "Literature Cited," p. 145.) Reports specifically dealing with rock alteration are those by Kelley and Kerr (1957) on argillization, Kerr and Hamilton (1958) on chromium-bearing mica clays, and Bodine and Kerr (1956) and Kerr (1956) on dolomitization. Numerous ore bodies of moderate tonnage in the Temple Mountain mineral belt were discovered and partly blocked out by drilling by the Atomic Energy Commission.

General studies of mineralogy were made by the Union Mines Development Corp. (F. M. Murphy, written commun., 1944), Gruner and Gardiner (1952), and Weeks and Thompson (1954). Hausen (1956, 1959) studied in detail the mineralogy and paragenesis of the Temple Mountain ores. Coleman and Delevaux (1957) determined the selenium content of some sulfide minerals collected in the district and identified the rare iron selenide, ferroselite, from the Calyx 8 mine. The sulfur-isotope composition of some Temple Mountain sulfides collected by Coleman and I. A. Breger was determined by Jensen (1958), who reported that the enrichment in the S^{32} isotope and broad spread of the $S^{32}:S^{34}$ ratios suggested that the sulfur was derived from H_2S produced by anaerobic bacteria.

References on the organic materials constitute most of the literature on the ore; the most significant of these are reports by Kerr and Kelley (1956), Kelley and Kerr (1958), Hausen (1959), Breger and Deul (1959), and Abdel-Gawad and Kerr (1961). Breger and Deul studied various organic materials from the district and concluded that the so-called "asphaltite" was derived from coal or coal extracts rather than from petroleum. The reports just cited generally support a petroliferous origin for the asphaltite.

Several reports of general interest refer to the Temple Mountain district. Gott and Erickson (1952) and Erickson, Myers, and Horr

(1954) noted the similarity between the trace-element content of uranium-vanadium ores of the Colorado Plateau and the trace-element content of petroleum. Shoemaker (1956, p. 161, 167, 168) discussed the Temple Mountain collapse structure as well as some other structures of the Colorado Plateau.

FIELDWORK AND ACKNOWLEDGMENTS

This report is based largely on work of Wyant and others in 1946 and 1947 and on studies by Hawley, Brooks, and others in 1956 and 1957. In 1947, Wyant, assisted by E. V. Stratton and G. V. Carroll, mapped the radioactivity and stratigraphy of the Moss Back Member at Flat Top (pl. 7) and at the Camp Bird 12 group ("South Workings," pl. 6), and E. B. Dingle sampled the Moss Back at approximately 100-foot intervals around Flat Top. This work was done primarily to determine if low-grade halos of mineralized rock surrounded ore bodies. Earlier, in the fall and winter of 1946, Wyant assisted W. L. Stokes in a detailed study of the Chinle stratigraphy near Temple Mountain.

In 1956 and 1957, studies were made in the Temple Mountain district as part of the investigation by the U.S. Geological Survey of the geologic relations of ore deposits in several parts of the San Rafael Swell. James G. Moore and Jules A. MacKallor assisted Hawley in the field from June to August 1956, and David B. Brooks assisted in the field and office from October 1956 to March 1957. During this time a map was made of the district (pl. 1), the Calyx 8 mine was mapped in detail (pl. 4), and less detailed studies were made of North Mesa 1, 2, and 5 mines (pl. 5) and other mines and prospects. A preliminary summary of this work, written by Hawley, was published in 1957.

We have also tried to compile and use, critically, some of the wealth of information that has been gathered by geologists of the Union Mines Development Corp., the Union Carbide Nuclear Co., and the Atomic Energy Commission. We are greatly indebted to the geologists and mining men of the Temple Mountain district for their cooperation in project activities and, more important, for many stimulating discussions of the geologic problems of the district. In particular we want to list the following employees of the U.S. Atomic Energy Commission: G. L. Chase, P. H. Dobbs, Y. W. Isachsen, W. S. Keys, R. W. Kopf, R. L. White, H. B. Wood, and R. G. Young; and these employees of the Union Carbide Nuclear Co.: John Herron, Gordon Irvine, Jr., and John Motica. Jess Abernathy, who has been affiliated with both Consolidated Uranium Co. and Union Carbide Nuclear Co., furnished geologic and historical data on the mines and freely discussed his ideas on the genesis and localization of the deposits.

We also acknowledge contributions by other geologists of the U.S. Geological Survey. The earlier work in the San Rafael Swell by I. J. Witkind, R. C. Robeck, H. B. Dyer, and their associates was a general guide throughout the investigation. The problems connected with the carbonaceous materials were discussed in the field with I. A. Breger, Maurice Deul, and J. M. Schopf. All the work was done on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

Most of the chemical analyses were made in the laboratories of the U.S. Geological Survey, and the analysts are credited in tables and in figures showing the results of analyses. Infrared spectra of carbonaceous materials were studied by L. D. Frederickson, Jr., of the Spectran Laboratories, Denver. Two ultimate analyses of asphaltite by the Clark Laboratory, Urbana, Ill., were furnished the project by A. P. Pierce, and most of the mill-pulp analyses were furnished by A. T. Miesch. Margaret Jones calculated the weighted averages used in table 4, and Theodore Botinelly and J. R. Houston, of the Geological Survey, made some of the mineral identifications.

ANALYSES

Samples of ore and of mineralized rocks, and concentrates of minerals and of carbonaceous materials, were analyzed in the U.S. Geological Survey laboratories in Denver and in Washington. The radioactivity and chemical analyses were made by radiometric, colorimetric, and gravimetric methods. The spectrographic analyses were made by a semiquantitative technique in which the presence or absence of each of more than 60 elements is determined from the photographic record of a single arcing of one sample (Myers and others, 1961). The results of the analyses made by the semiquantitative spectrographic method are reported as numbers representing limits of concentration defined by a set of standards, as shown below:

Number reported (percent)	*Limits of concentration defined by standards (percent)*
7	10.0–4.6
3	4.6–2.2
1.5	2.2–1.0
.7	1.0–0.46
.3	.46–0.22
.15	.22–0.1
.07	.1–0.046
And so forth	And so forth

Amounts present in excess of 10 percent are reported as major constituents (M). The minimum amounts detectable by the semiquantitative method are shown in table 1.

TABLE 1.—*Visual detection limits, in percent, for the elements determined by the semiquantitative spectrographic method*

[Limits listed are those of the U.S. Geol. Survey lab., Washington, D.C. Although the list refers to the visual detection limits of the elements for 1956, during which period most of the samples were analyzed, sensitivities for other periods are sufficiently similar for the purposes of this report. A different exposure in the red part of the spectrum is required for the sensitivities shown in parentheses]

Si	0.005	Dy	0.006	Pt	0.003
Al	.0001	Er	.003	Rb	7. (0.007)
Fe	.0008	Eu	.003	Re	.04
Mg	.00003	F [1]	.08	Rh	.004
Ca	.01	Ga	.001	Ru	.008
Na	.01 (0.0003)	Gd	.006	Sb	.01
K	.1 (0.005)	Ge	.001	Sc	.0005
Ti	.0005	Hf	.007	Sn	.001
P	.07	Hg	.08	Sr	.001
Mn	.0007	Ho	.001	Sm	.008
Ag	.00001	In	.0004	Ta	.1
As	.01	Ir	.03	Tb	.01
Au	.001	La	.003	Te	.08
B	.005	Li	.01 (0.00003)	Th	.05
Ba	.0005	Lu	.005	Tl	.04
Be	.00005	Mo	.0005	Tm	.001
Bi	.005	Nb	.001	U	.08
Cd	.005	Nd	.006	V	.001
Ce	.03	Ni	.001	W	.05
Co	.001	Os	.1	Y	.001
Cr	.0006	Pb	.001	Yb	.0001
Cs	.8 (0.01)	Pd	.003	Zn	.008
Cu	.00005	Pr	.01	Zr	.0008

[1] A separate exposure is required for the fluorine estimation.

Chemical compositions of uranium deposits (table 3) and of ore and barren rocks (table 4) are averages. Most of the averages are geometric means weighted according to the tonnage represented by the sample. The values reported are the midpoints of the ranges within which the calculated values fall. The overall average composition of the ore (table 4) is a list of geometric means weighted according to the 1948–56 production of the mines. These average values are reported to the first two figures of the calculated average and not as the midpoints.

Analyses of carbonaceous materials are presented in tables 10, 11, and 12. The organic components were usually burned off prior to analysis, and the remaining ash was analyzed for inorganic components. Partial to complete volatilization of some elements such as arsenic may have taken place during ashing (Bell, 1960, p. 49), but for most elements the loss involved in a burning or dry-ashing technique was probably not significant (A. T. Myers, oral commun., 1959). The analyses are reported directly and also on a recalculated basis in terms of the original carbonaceous substance. Dual sample numbers are given in the tables of analyses; the number preceded by a letter or letters is the field number, and the six-digit number is the laboratory number.

GEOLOGY

Sedimentary rocks ranging from Permian to Jurassic in age and totaling about 2,800 feet in thickness are exposed in the Temple Mountain district (pl. 1). Locally these rocks are covered by a thin layer of very young, unconsolidated sediments, which include eolian deposits east of the Reef, alluvium in valleys, and colluvium on the steep slopes of Temple Mountain. The sedimentary rocks are chiefly of continental or near-shore origin; however, the Kaibab Limestone and the Sinbad Limestone Member of the Moenkopi Formation were deposited by eastward-transgressing seas.

The rocks dip generally southeast; the dip lessens westward toward the axis of the San Rafael anticline, which is the controlling geologic structure of the San Rafael Swell. Crossfolds, collapse structures, and high-angle normal faults locally complicate the generally simple structural picture.

STRATIGRAPHY

PERMIAN SYSTEM

The Coconino Sandstone of Permian age is the oldest exposed formation in the district, but drilling about 7 miles north of Temple Mountain has shown that about 3,400 feet of older rocks lies between the base of the Coconino Sandstone and the Precambrian basement. Pre-Permian rocks include thick limestones, and they generally reflect marine rather than continental deposition.

Coconino Sandstone.—Only the uppermost 80 feet of the thick Coconino Sandstone is exposed in the Temple Mountain district; the exposures are in the canyons north of Temple Mountain. The total thickness of the Coconino is unknown, but it probably approximates the 660 feet reported in the north part of the San Rafael Swell (Baker, 1946, p. 49). Diamond-drill holes in and near the Temple Mountain collapse structure penetrated only the upper part of the formation.

The Coconino is composed almost entirely of light-colored sandstone. The topmost 40–60 feet is a fine- to medium-grained slabby flat-bedded sandstone containing scattered silicified fossil fragments. It is underlain by fine-grained sandstone in large-scale high-angle crossbeds.

The flat-bedded sandstones at the top of the Coconino are apparently gradational with the Kaibab Limestone and probably represent strata reworked by the transgressing Kaibab sea.

Kaibab Limestone.—The Kaibab Limestone of Permian age crops out as a thin ledge above the Coconino in the canyons north of Temple Mountain; its thickness averages about 25 feet and ranges from zero to about 40 feet. Although the Kaibab probably underlies most of the district, drilling shows that it is very thin or absent beneath the Temple Mountain collapse structure.

Buff to gray dolomitic limestone is the overall major component of the Kaibab; but in the lower part of the unit, siltstones and sandstones also are abundant. Light-colored chert in irregular masses, nodules, and layers is abundant in the limestone, and some of the nodules have vuggy centers containing petroleum. The following section is typical of the Kaibab in North Temple Wash:

Section of Kaibab Limestone measured 4,500 feet northeast of the bench mark on Temple Mountain

	Thickness (ft)
Moenkopi Formation.	
Kaibab Limestone:	
Limestone, dolomitic, light-gray to buff; contains chert as patches, layers, and nodules; massive outcrop; individual beds 3–4 ft. thick. Lower 5.5 ft. is petroliferous	17.4
Limestone, dolomitic; numerous chert nodules cause characteristic knobby weathering; nonpetroliferous	3.5
Siltstone, dolomitic, gray, and thin layers of dolomitic limestone	5.5
Siltstone, slightly dolomitic, gray; selenite veinlets on shaly partings	3.5
Sandstone and siltstone; interlayered beds as much as 2 ft. thick. Sandstone is fine grained, petroliferous. Siltstone is greenish and forms irregular slabby-weathering beds	5.5
Total	35.4
Coconino Sandstone.	

The upper contact of the Kaibab is disconformable; the basal conglomerates and standstones of the overlying Moenkopi Formation were deposited on an irregular surface cut on, or scoured into, the Kaibab.

TRIASSIC AND JURASSIC SYSTEMS

MOENKOPI FORMATION

The Moenkopi Formation of Early and Middle(?) Triassic age is exposed throughout most of the northwest half of the district. In general it forms slopes but resistant sandstone and limestone beds in the lower three-quarters of the formation erode to rounded or vertical cliffs.

Geologic mapping shows that the Moenkopi averages about 600 feet in thickness and thus generally confirms a thickness of 613 feet measured on the north side of Temple Mountain by J. H. Stewart and C. H. Scott (written commun., 1953). The formation can be divided into three parts: the lower part, which averages about 120 feet in thickness; the middle part, or Sinbad Limestone Member, which is slightly less than 50 feet thick; and the upper part, which is about 430 feet thick. Only a twofold division is shown on the map (pl. 1); the Sinbad Limestone Member and the upper part are shown as a single unit.

The lower part of the Moenkopi Formation is composed mostly of greenish pyritic fissile siltstone beds. The basal part, as much as 20 feet thick, consists of intergrading massive chert-pebble conglomerate and fine-grained slabby-weathering standstone. It is overlain by the siltstone strata, which contain sparse massive interbeds of petroliferous fine-grained sandstone and thin interbeds of limestone. Erosion of the lower part of the Moenkopi creates a steep slope, and weathering causes the rock to become yellowish brown. Selenite is abundant in the weathered rock. The contact with the overlying Sinbad Limestone Member is sharp and apparently conformable; it might, however, be considered gradational because of the greater abundance of limestone interbeds in the siltstone strata near the Sinbad Member.

The cliff-forming Sinbad Limestone Member is composed mostly of dolomite but also contains subordinate amounts of siltstone and fine-grained sandstone. The dolomite consists of yellowish-tan locally oolitic beds averaging about 6 inches in thickness; both the dolomite and the sandstone are locally crossbedded. Petroleum is widespread but erratically distributed in the Sinbad Limestone Member, as are both nodules and cylindrical masses of asphalt, which are as much as one-fourth inch across. Limonite- or hematite-cemented nodules are common, and small crystals of galena or other sulfides are trace constituents of the rock. At least locally, the Sinbad is anomalously radioactive and selenium bearing. The base of the Sinbad was sampled 7,000 feet west of Temple Mountain; a 2-foot chip contained 0.006 percent eU (equivalent uranium) and 38 ppm (parts per million) selenium. A 12-foot chip sample collected in the lower part of the Sinbad 10,000 feet northwest of Temple Mountain contained 0.005 percent eU and 3 ppm selenium. The nodular asphalt of the Sinbad Limestone Member is slightly uraniferous.

The upper part of the Moenkopi is composed mainly of alternating conformable strata of fissile siltstone and silty sandstone; the beds of silty sandstone average about 3 feet in thickness and crop out as rounded ledges. Except in the northeast part of the district, most of the siltstone and silty sandstone is red brown. Interspersed with the siltstone and silty sandstone in the lower 250 feet of the unit are beds of ledge-forming fine-grained light-colored sandstone averaging about 20 feet in thickness. These light-colored sandstone beds are invariably petroliferous; they have disconformable basal contacts with the scoured surface of the underlying silty sandstones and siltstones. The scour features are small, and inasmuch as the light-colored sandstones are relatively continuous, they, as well as the basal

Sinbad contact, were used in determining the geologic structure in Moenkopi outcrop areas.

A zone of light-colored rocks is present in the upper part of the Moenkopi in the northeast part of the district, but it was not mapped. The zone cuts across bedding at a small angle and thickens northward from a pinchout near the northeast corner of Temple Mountain. The zone includes green pyritic siltstone beds and massive locally disconformable sandstone beds, which probably contain more petroleum than do similar sandstone beds outside the zone. These features, particularly the fact that the green and red-brown color boundary cuts across lithologic units, clearly indicate that the zone is a result of alteration. The zone is displaced by normal faults, which it therefore predates; it does not extend to the Temple Mountain collapse structure and is probably unrelated to that structure.

The Moenkopi Formation is disconformably overlain by the Chinle Formation. No recognizable angular discordance between the formations was seen in the district, but regional studies indicate that the Moenkopi was slightly warped and partly eroded before the deposition of the Chinle Formation.

CHINLE FORMATION

The Chinle Formation, of Late Triassic age, is exposed along a northeast-trending belt just within the San Rafael Reef; the Temple Mountain, Monitor Butte, and Moss Back Members are also exposed on Flat Top, a mesa in the west part of the district. The Chinle Formation averages about 360 feet in thickness and, as mapped, consists of the Temple Mountain, Monitor Butte, Moss Back, and Church Rock Members.

TEMPLE MOUNTAIN AND MONITOR BUTTE MEMBERS

The Temple Mountain and Monitor Butte Members reach a maximum thickness of about 60 feet on the south side of Flat Top. They range from 12 to 40 feet in thickness along the main outcrop belt and thin generally toward the northeast. As they are thin and locally intergrading, the two members are not separable and were mapped as one unit. They generally form a steep slope below the Moss Back Member; resistant beds at the base, which are assigned to the Temple Mountain Member, form a persistent cliff as much as 20 feet high in the part of the district northeast of South Temple Wash.

The Temple Mountain and Monitor Butte Members are composed mostly of poorly bedded typically mottled red, pale-green, and purple mudstone and siltstone; locally they contain thin beds of fine-grained ripple-marked red sandstone and lenses of gray to green coarse-grained sandstone and conglomerate. Sandstone, conglomerate, and massive well-indurated siltstone tend to be more abundant in the lower part of the unit and also generally more abundant northeast along the main outcrop belt. The two measured sections of the Temple Mountain and Monitor Butte are typical of the unit in the south and north parts of the district, respectively:

Section of Temple Mountain and Monitor Butte Members, measured 5,500 feet west-southwest of Camp Bird 12 mine

Moss Back Member of Chinle Formation.

Monitor Butte and Temple Mountain Members:	*Thickness (ft)*
Mudstone, red and green; pervasively bleached green in upper 3 ft	5.0
Siltstone, mottled red, green, and purple, massive; forms a distinct ledge	9.0
Mudstone, red; contains minor lenticular areas of green and purple mudstone	14.0
Sandstone, white, coarse; composed of subangular quartz grains	2.0
Mudstone, grayish-red, friable	6.0
Mudstone, nonfissile, grayish red-purple (5*RP* 4/2)[1]	.5
Total	36.5

Moenkopi Formation. Upper part is somewhat fissile grayish-red (10*R* 4/2)[1] siltstone.

[1] Colors from "Rock-Color Chart" (Goddard and others, 1948).

Section of Temple Mountain and Monitor Butte Members, measured north of intersection of North Temple Wash with Moss Back outcrop

Moss Back Member of Chinle Formation.

Monitor Butte and Temple Mountain Members:	*Thickness (ft)*
Mudstone, green; cut by numerous gypsum veinlets; more resistant than underlying siltstone and mudstone	3.5
Siltstone and mudstone, mottled red, purple, and green, poorly bedded, slope-forming	3.5
Siltstone, mottled red, purple, and green, ledge-forming; contact with lower unit is irregular over several inches	3.5
Siltstone and conglomerate, purple and red; contains quartz pebbles as much as ½ in. across and hematite-impregnated pebbles; ledge forming; sharp contact with underlying Moenkopi; purple colors cross into Moenkopi along low-angle fractures	5.5
Total	16.0

Moenkopi Formation.

Sandstone lenses representing channel fills are found in the Temple Mountain and Monitor Butte along the main outcrop belt in the south part of the district and also on Flat Top (pl. 1). The paleochannel on Flat Top is at the base of the unit; it trends northwest and is composed of poorly sorted coarse-grained sandstone containing local concentrations of fusainlike carbonaceous materials. The sandstone is locally radioactive.

The mottled red, purple, and pale green colors typical of the Temple Mountain and Monitor Butte are in part the result of regional alteration. The alteration was partly controlled by bedding-plane and related low-angle fractures, which are most common within a few feet of the Monitor Butte–Moss Back contact and die out at depth. Mottling is the most obvious effect of the alteration, but uraniferous chert-carbonate veins containing small amounts of sulfides are locally present in the low-angle fractures which controlled the alteration. The distribution of the mottled rocks of the Temple Mountain and Monitor Butte is apparently unrelated to the Temple Mountain collapse structure.

In most places the contacts of the unit are disconformable and well defined. In the north part of the district, the basal part is made up of ledge-forming siltstone beds containing scattered coarse sand grains and lenses of sandstone and conglomerate; here its lithology contrasts strongly with that of the fissile siltstones typical of the upper part of the Moenkopi Formation. In the south part of the district, where sandstones and conglomerates are not as abundant, purple color, scattered sand grains, and lesser fissility of mudstones of the Temple Mountain and Monitor Butte Members help define the lower contact. In most places the upper contact has sandstone or conglomerate of the Moss Back resting disconformably on the mudstone of the Monitor Butte. Where the Monitor Butte and the Moss Back are mudstone, the two can be distinguished by scattered quartzite and chert pebbles in the Moss Back.

MOSS BACK MEMBER

The Moss Back Member, more resistant to erosion than either the underlying Temple Mountain and Monitor Butte Members or the overlying Church Rock Member, forms a prominent light-colored bench along the main Chinle outcrop belt and also caps Flat Top in the western part of the district. It is composed chiefly of lenticular and intergrading strata of sandstone and conglomerate.

The sandstones and conglomerates of the Moss Back Member were deposited on a surface of low relief by northwest-flowing shifting streams. In the Temple Mountain district, during at least part of Moss Back time, the streams were aggrading and actively building up their channels. The channels are now preserved as local relatively thick units or facies within the Moss Back. The intraformational occurrence of the paleochannels and a local convex-upward shape contrast with the occurrence and shape of many paleochannels found elsewhere in the Moss Back Member in the San Rafael Swell, and which fill scours cut down into the Moenkopi Formation are convex downward. The paleochannels in the Temple Mountain district are similar to the scour or erosional type channels in that they are hosts to valuable uranium deposits.

Thickness

The Moss Back Member ranges in thickness from slightly less than 60 feet near the Temple Mountain collapse structure to about 130 feet in a drill hole (not shown on pl. 1) in South Temple Wash; the average thickness in the district is about 90 feet. At Temple Mountain a poorly defined north-trending belt of thick Moss Back, suggested by 100-foot isopachs shown in figure 4, extends about due north from near the Calyx 1 mine across the Calyx Bench to the east part of North Temple Mountain. Because of a rounder, less clifflike outcrop, the Moss Back seems markedly thinner south of South Temple Wash, but in exposures and in cores from drill holes it has its usual thickness.

Stratigraphy

The Moss Back Member can be subdivided lithologically into four units or facies, largely as proposed by W. L. Stokes and D. G. Wyant (written commun., 1946, 1953). The four facies, each named for its principal rock type, are (1) the conglomeratic sandstone, (2) the massive sandstone, (3) the limestone-pebble conglomerate, and (4) the platy sandstone facies. The rock units generally occur in this numerical order from the base to the top of the Moss Back; locally, however, one or more facies are absent or the facies intertongue, and, consequently, the order is different or more complex. In most places the contacts between the facies are evident from lithologic changes, such as the changes in the type and relative abundance of pebbles and of calcite cement. In some places the contacts are indicated by mudstone splits.

Some of the variations in thickness and distribution of the facies are shown graphically on plate 2; examples of the detailed facies relations in selected areas of mineralized rock are shown on plates 5–7.

Although a subordinate component, mudstone is abundant in all the facies, especially near the base of the conglomeratic sandstone unit and also in the upper part of the massive sandstone unit. It occurs in layers, lenses, and fragments in and between the facies. The fragments range in size from flakes or galls one-eighth inch or less across to blocks as much as 2 feet across. Mudstone containing scattered quartzose pebbles, locally referred to as mudstone conglomerate, commonly caps or floors ore-bearing sandstone; as the pebbles decrease or increase in abundance, the rock grades into mudstone or conglomerate.

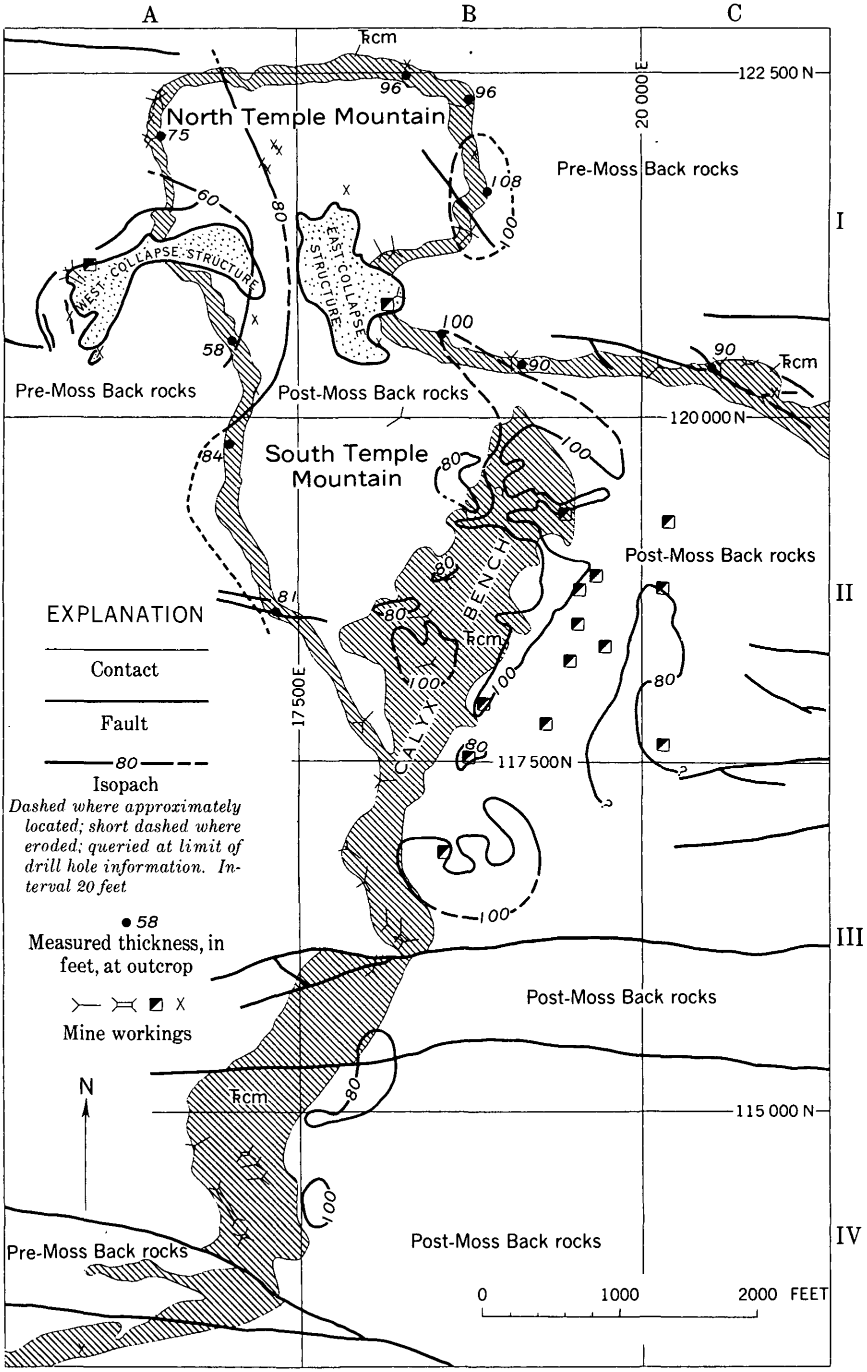

FIGURE 4.—Isopach map of Moss Back Member, Temple Mountain area. Thickness of member on Calyx Bench from U.S. Atomic Energy Commission drill holes. Areas where Moss Back crops out are indicated by oblique-line pattern.

Coaly materials are locally found in the mudstone, and fragments of reedlike coalified wood are abundant in thin mudstone splits.

The conglomeratic sandstone facies, commonly the basal unit of the Moss Back, is composed chiefly of conglomeratic sandstone and subordinately of mudstone conglomerate, fine- to medium-grained sandstone, and pebble conglomerate. The rounded pebbles are, in order of abundance, red chert, gray quartzite, and quartz of various colors. The conglomeratic sandstone, fine-grained sandstone, and pebble conglomerate are in most places well cemented by calcite; they are locally petroliferous. Brown and gray partly silicified logs as much as 2 feet in diameter are relatively abundant. The outer parts of large logs are commonly composed of vitrain.

The overlying massive sandstone facies is composed mainly of fine- to medium-grained white-weathering sandstone and subordinately of mudstone and conglomerate. Most of the sandstone in the unit is characterized by high-angle planar or trough cross-stratification (McKee and Weir, 1953, p. 386–387), but erosion of the unit as a whole produces a rounded steep massive outcrop, which suggests the name of the facies. The massive almost-white strata of the unit are clearly visible at a distance.

Outside areas of altered and mineralized rock, the sandstone is calcareous and is commonly, perhaps uniformly, petroliferous. In areas of altered or mineralized rock, it is largely noncalcareous and nonpetroliferous, but it does contain scattered secondary carbonates and blebs of interstitial asphalt. On an average, coaly materials are much less abundant in the massive sandstone facies than in either the underlying or overlying facies. Scattered pebbles are locally abundant near the tops and bottoms of sandstone beds; the pebbles are chiefly chert, quartzite, and altered silicified limestone.

The sandstones of the unit are quartzose and argillaceous; they contain small amounts of feldspar, detrital mica, fine-grained rock fragments, and widely varying amounts of calcite (table 2). The quartz grains are rounded, but most have subhedral to euhedral overgrowths. Kaolinite and mica clays (table 2) commonly are interstitial but locally replace detrital grains; mica clays[1] also occur in scattered mudstone galls in the sandstone. Petroleum or asphalt (not tabulated in the analyses) is seen microscopically as coatings on clay minerals and rarely as interstitial to the sand grains.

The limestone-pebble conglomerate unit generally overlies the massive sandstone unit; locally, as on the east side of Flat Top (section

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[1] Mica clays, in this report, are the fine-grained claylike components that have micaceous habit and noticeable birefringence. The distinction of mica clays and kaolinite in thin section was made on the bases of birefringence and form. The kaolinite has very low birefringence, and it has a massive or vermicular rather than micaceous form.

TABLE 2.—*Modal analyses, in volume percent,*[1] *of sandstone from the massive sandstone unit of the Moss Back Member of the Chinle Formation*

	1	*2*	*3*
Detrital grains:			
Quartz	70	68	82
Potassic feldspar	3	2	3
Fine-grained rock fragments	2	3	2
Plagioclase	2	1	1
Muscovite	1	Trace	Trace
Others (zircon, for example)	Trace	Trace	Trace
Cement and interstitial materials:			
Kaolinite	6	5	9
Fine-grained mica clays	10	4	3
Calcite	6	17	0

[1] Pore space not counted.

SOURCE OF SAMPLES

1. Sandstone, (field No. TM-103A) from 11,000 ft east-northeast of North Temple Mountain; percent U=0.0017.
2. Sandstone (field No. TM-383) collected from nearly fresh talus blocks, North Temple Wash, 4,000 ft east of Vanadium King 1 mine; percent U=0.0008.
3. Sandstone (field No. TM-370), in part crossbedded, containing some limonite probably after pyrite, 1,000 ft east of Vanadium King 1 mine; percent U not determined.

B–B′, pl. 7), the two units intertongue. Major rock types in the conglomerate unit, in order of abundance, are limestone-pebble conglomerate, calcareous medium-grained sandstone which weathers brown, and sandstone which weathers white and is similar to the sandstone typical of the massive sandstone unit. The unit generally forms a steep cliff and weathers to a brown color. Rounded quartzose pebbles are present in the conglomerate but are not as abundant as either flat to rounded limestone pebbles or pebbles of limy siltstone. Coaly materials are more abundant than in the massive sandstone facies but are not as abundant as in the basal conglomeratic sandstone of the Moss Back Member. Although the highly calcareous rocks of the unit are nonpetroliferous, they locally grade into slightly calcareous rocks that are petroliferous (section *C–C′*, pl. 5).

As shown diagrammatically on plate 2, the limestone-pebble conglomerate is virtually absent in the Temple Mountain area from the south end of the Calyx Bench to a point just northeast of the Calyx Bench. Limestone-pebble conglomerate and related rocks form the caprock on the northeast, west, and south parts of Flat Top (pl. 7).

The uppermost unit, the platy sandstone, is composed mainly of gray or faintly greenish-gray thin-bedded calcareous sandstone having planar and trough crossbeds. Light-colored sandstone beds similar to those of the massive sandstone unit are locally present. The sandstones are locally petroliferous and, on the Calyx Bench, contain pyritic nodules or limonite-cemented masses.

The upper contact of the Moss Back Member is difficult to locate exactly because the platy sandstone facies of the Moss Back Member resembles the basal sandstones of the Church Rock Member. In general, however, the basal sandstones of the Church Rock are siltier and lack the quartzose pebbles found in the Moss Back. Where unaltered, the basal sandstones of the Church Rock are typically red or purple.

Sedimentary trends

Measurement of the orientation of crossbeds and other sedimentary structures at many places on the Colorado Plateau has shown that the Moss Back Member generally was deposited in a northwest direction (Poole and Williams, 1956, fig. 50*B* and p. 231). Detailed studies of crossbeds and orientation of fossil logs and paleochannels in parts of the Temple Mountain district indicate that streamflow was slightly west of north at Temple Mountain and northwest on Flat Top and in the south part of the district.

The use of crossbeds to determine direction of sediment transport has been summarized by Poole and Williams (1956, p. 229–231), who stated that the average dip direction of a sufficient number of crossbeds indicates the direction of sediment transport; for the Moss Back, this is the direction of streamflow. Single crossbeds are represented by vectors from which the effects of regional dip have been removed. The vectors are added, either graphically or trigonometrically, and the resultant is the average dip direction. The crossbeds may be examined statistically in other ways; for example, their variance can be determined by the consistency ratio of Reiche (1938, p. 913). This ratio ranges from 0 to 1. If all crossbeds have the same dip direction, the factor is 1, if no two are alike, the consistency ratio is 0.

Average dip directions at Temple Mountain determined in three separate studies were N. 13° W., N. 5° W., and N. 42° W. A study of 85 crossbeds in the lower part of the Moss Back around Temple Mountain (fig. 5, upper diagram) showed the direction N. 13° W., a dip of 18°, and a consistency ratio of 0.42 (calc. by F. G. Poole, 1958). A study of 96 crossbeds in the Calyx 8 mine showed the direction N. 5° W., a dip of 18°, and a consistency ratio of 0.52 (fig. 5, lower diagram). A third study, by A. C. Gorveatt (written commun., 1953; recalc. by F. G. Poole, 1958), showed the direction N. 42° W., a dip of about 12°, and a consistency ratio of 0.30; exact location of this study is not known, but most likely it was on the upper sandstones of the Moss Back on Temple Mountain. The data obtained from all three studies are fairly consistent with the north-northwest direction estimated by W. L. Stokes from crossbeds and logs.

The orientations of 131 fossil logs in the south part of district were determined as a special study by J. G. Moore. The log orientations are plotted on a circular diagram (fig. 6), and their locations and orientations are shown on plate 1. The logs are, on an average, oriented N. 56° W. (calc. by F. G. Poole, 1958), however, the significance of this figure is uncertain for two reasons: (1) logs in contemporary streams

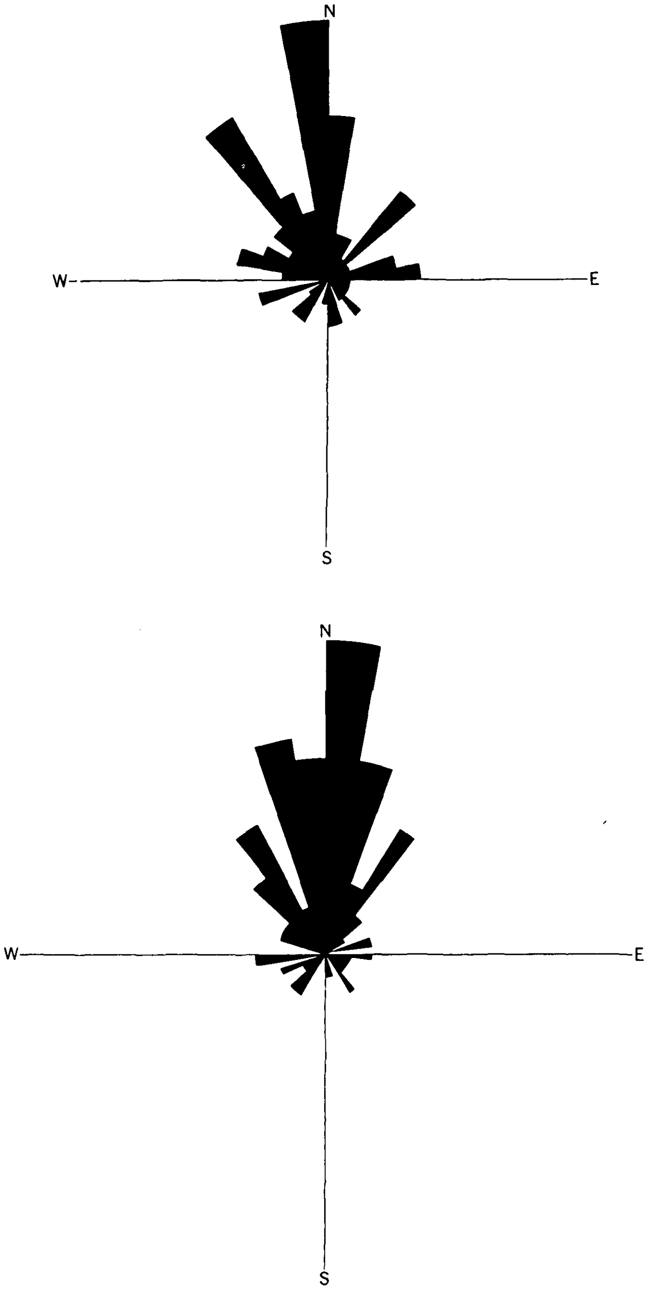

FIGURE 5.—Dip directions of crossbeds in the Moss Back Member in the Temple Mountain area (upper) and in the Calyx 8 mine (lower).

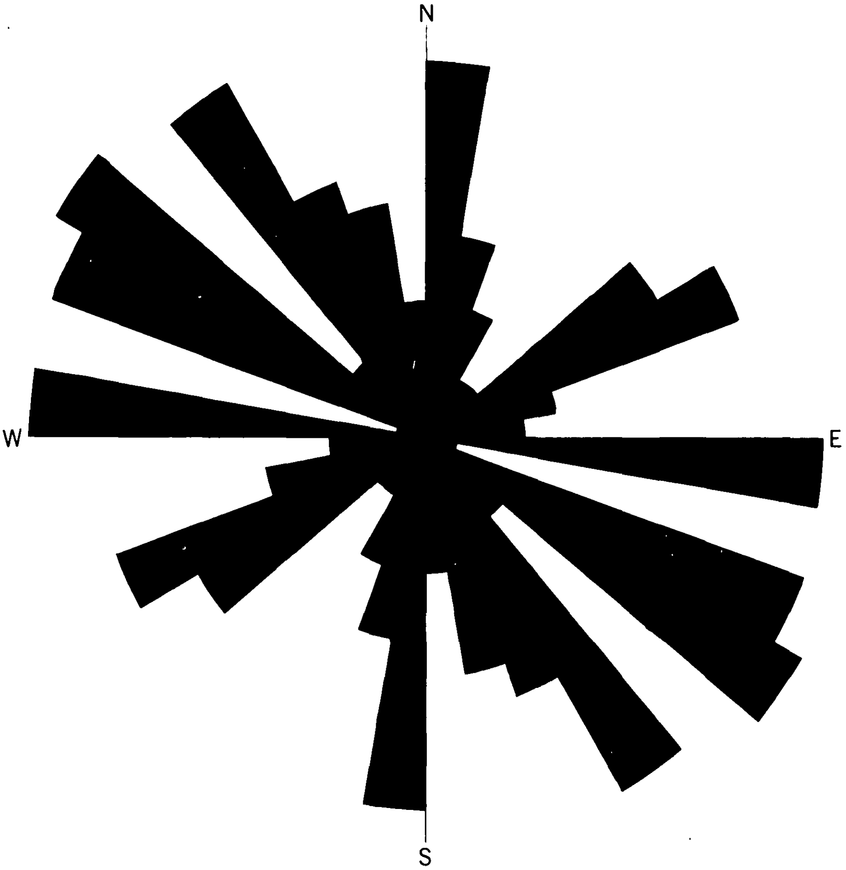

FIGURE 6.—Orientation of fossil logs in the Moss Back Member in the south part of the Temple Mountain district.

appear to have a bimodal distribution—that is, they tend to be oriented either parallel or perpendicular to the direction of streamflow—and (2) the measurements show an obvious lack of consistency (fig. 6). Probably, though, the average orientation supports a general northwest flow for streams that deposited the Moss Back.

A northwest trend of paleostreamflow near Flat Top is suggested by the orientations of the dip directions of planar crossbeds and of axes of trough crossbeds that were observed during the detailed mapping of Flat Top (pl. 7). It is further confirmed by the orientation of thick sandstone units.

Channel deposits

The channel deposits of the Moss Back Member at Temple Mountain differ from those that have commonly been described from the Moss Back Member. The most conspicuous channel deposits of the Moss

Back Member fill scours cut down into the lower part of the Chinle or Moenkopi Formations, and this type of channel is the host of valuable ore deposits in other parts of the San Rafael Swell. Only small channels of this type are found in the Temple Mountain district.

A second, less conspicuous channel deposit is represented by thick sandstone or conglomerate lenses within the Moss Back Member. This type, which formed in the massive sandstone facies of the Moss Back Member, is the host of most of the uranium in the Temple Mountain district. In places it fills scours cut into lower facies of the Moss Back Member, but this type also may be convex upward, and in typical exposures it is marked by a thick lens of the channel facies and by thinner than normal sections of the underlying and overlying facies.

Channel deposits of the massive sandstone facies, the main ore-bearing unit at Temple Mountain, are well formed in the district. Two large paleochannels are found at Temple Mountain, another is at Flat Top, and others are in areas of unmineralized rock. In an area of ore deposits, the largest of the paleochannels, the Temple Mountain channel, trends south-southeast at least 4,000 feet from Temple Mountain and is inferred to extend south under the thick cover of younger rocks. It is about 3,500 feet wide on the Calyx Bench, where its southwest boundary is just south of the North Mesa group of mines and its northeast boundary is about 1,000 feet east of the Vanadium King 1 mine. The massive sandstone facies is as much as 48 feet thick in the channel compared to about 20 feet thick outside of it. The limestone-pebble conglomerate unit, which in most places overlies the massive sandstone unit, thins on both flanks of the channel and is absent over much of it (as shown diagrammatically on pl. 2). The Temple Mountain channel may be reflected, to some extent, by the increase in the total thickness of the Moss Back, which is evident from the 100-foot isopachs in a north-trending zone on the Calyx Bench and North Temple Mountain (fig. 4).

The second major paleochannel of the Temple Mountain area is exposed in the Camp Bird 12 or "South Workings" area. Like the Temple Mountain channel, it trends about north-northwest. Its northeast boundary, exposed north of the mine workings, is marked by an abrupt thinning of the massive sandstone facies, which is as much as 30 feet thick in the center of the channel; the southwest boundary is not exposed. The Temple Mountain and Camp Bird 12 channels are separated by a 1,000-foot interval along the outcrop in which the massive sandstone facies is less than 10 feet thick.

The Flat Top channel trends northwest; it is about 1,600 feet wide and as much as 40 feet thick. Its northeast boundary is marked by the intertonguing and pinchout of the massive sandstone unit in the conglomeratic sandstone in the northeast part of the mesa (sections *A–A′*

and *B–B′*, pl. 7). Its southwest boundary is more indefinite but is probably near the south end of the mesa, where the facies thins rapidly.

These thickened sections of the massive sandstone facies of the Moss Back contain most of the valuable ore deposits of the district. Other large paleochannels in the same facies, unmineralized but otherwise similar, are exposed on the prominent point about due south of Flat Top and on the point east-northeast of Temple Mountain (pl. 1).

CHURCH ROCK MEMBER

The Church Rock Member of the Chinle Formation crops out as a steep slope immediately below the massive cliff formed by the Wingate Sandstone. It ranges from 200 to almost 280 feet in thickness.

Red to purplish siltstones and fine-grained sandstones make up most of the unit, but light-colored sandstones and limestone-pebble conglomerates are locally present. One sandstone- and conglomerate-bearing unit, known informally as the black ledge, is persistent throughout much of the district but was not mapped. The black ledge is as much as 20 feet thick and consists of white to pinkish-gray calcareous sandstone, which weathers to a dark color, and buff to gray limestone-pebble conglomerate, which also weathers dark. It is underlain by a mottled calcareous siltstone containing small calcite nodules. The base of the black ledge ranges from 80 to 120 feet above the top of the Moss Back Member.

Rocks in the Church Rock Member have been extensively bleached or otherwise altered on Temple Mountain (pl. 1); in addition, the uppermost few feet of the Church Rock, immediately below the Wingate contact, is bleached at many other places. The bleaching was mapped only at Temple Mountain.

The contact between the Chinle Formation and the overlying Wingate Sandstone is apparently conformable; it is distinct except where masked by extensive dolomitic alteration on Temple Mountain.

WINGATE SANDSTONE

The Wingate Sandstone, of Late Triassic age, forms a nearly vertical cliff above the Chinle Formation. It is about 360 feet thick except in the southernmost part of the district, where it averages about 330 feet in thickness.

The Wingate is composed chiefly of fine-grained sandstone in high-angle planar medium- to large-scale crossbeds. The basal part contains scattered coarse frosted sand grains. The Wingate is petroliferous on Temple Mountain but rarely so in other parts of the district.

The Wingate Sandstone is altered throughout the district. On Temple Mountain it is bleached and almost white, and locally it is dolomitized. Elsewhere in the district it is less altered and is mainly pale yellowish white. Nowhere in the district is the sandstone the pale orange that is typical of unaltered Wingate found in other parts of the San Rafael Swell.

The Wingate Sandstone is overlain disconformably by the Kayenta Formation of Late Triassic(?) age, which in turn is overlain by the Navajo Sandstone of Triassic(?) and Jurassic age. These three formations constitute the Glen Canyon Group and form the massive San Rafael Reef. The more easily eroded Carmel Formation, of Middle and Late Jurassic age, overlies the Navajo Sandstone and crops out east of the Reef.

KAYENTA FORMATION

The Kayenta Formation averages about 220 feet in thickness. It consists mainly of interlayered beds of light-colored massive- to slabby-weathering crossbedded sandstone and subordinately of beds of siltstone and limestone-siltstone-pebble conglomerate. The crossbedding of the Kayenta Formation contrasts with that of the underlying Wingate Sandstone in type and in scale. Most of the Kayenta Sandstone is in low-angle, tangential small- to medium-scale crossbeds rather than in the high-angle large-scale type. The type of crossbedding and the occurrence of small intraformational scours filed with conglomerate suggest a fluviatile origin for the Kayenta.

Petroleum is less abundant in the Kayenta than in the Wingate. Notable concentrations of petroleum were observed in only the upper part of the Kayenta in North Temple Wash.

The upper and lower contacts of the Kayenta Formation are locally disconformable. Both contacts can be mapped accurately at a distance because of the contrast of thin bedding and dark weathered color of the Kayenta with the more massive bedding and lighter color of both the Wingate and Navajo.

NAVAJO SANDSTONE

The Navajo Sandstone, slightly more than 600 feet thick, is composed mainly of light-colored fine-grained sandstone and contains minor amounts of mudstone and discontinuous beds of limestone or dolomite. The lower part of the Navajo Sandstone is nearly structureless; the upper part is crossbedded on a medium to large scale in simple sets (McKee and Weir, 1953, p. 387).

The Kayenta and Navajo, like the Wingate, have been bleached and otherwise altered in the district and the original red color has been largely obliterated. Limestone beds in the Navajo have probably been dolomitized as have masses of sandstone as much as 4–5 feet across. The small masses of dolomitic sandstone resemble much larger masses found in the Wingate Sandstone on Temple Mountain.

Epigenetic green, chromium-bearing(?) mica clays impregnate the Kayenta locally in South Temple Wash and the Navajo and Kayenta in North Temple Wash.

CARMEL FORMATION

Only the lower part of the Carmel Formation is exposed in the district. The exposed rocks consist of red siltstone, purplish limestone, and very fine grained red to purple calcareous sandstone. According to Baker (1946, p. 73), the Carmel is 230 feet thick at Straight Wash, about 12 miles northeast of the district.

STRUCTURE

The Temple Mountain district is on the southeast flank of the San Rafael anticline. Within the district the rocks strike generally N. 55° E., subparallel to the trend of the major anticlinal axis in the south part of the San Rafael Swell; they dip 2° to more than 15° SE. The significant structures of the district, which are all superimposed on the general southeastward homoclinal dip, are a monoclinal flexure, crossfolds (or crosswarps), normal faults, and collapse structures. The crossfolds are folds of small amplitude that trend generally northwest at a large angle to the axis of the San Rafael anticline. The collapse structures are nearly vertical pipelike masses of altered rock, roughly oval in plan, that possibly formed by gravitational collapse of rocks into voids caused by solution. They are spatially, and probably genetically, related to the crossfolds. The normal faults cross the grain of the regional and local folds and are probably younger than either crossfolds or collapse structures.

FOLDS

Folds of the district are oriented either subparallel or at large angles to the generally northeast strike of the rocks. The major paralleling structure is a monocline that coincides in part with the San Rafael Reef. The fold is best shown (pl. 1) by a belt of relatively steep dips, which is bounded approximately by the 5,400-foot and 4,000-foot structure contours on the base of the Chinle Formation.

Folds that are oriented at large angles to the regional strike are termed crossfolds or crosswarps. The crossfolds trend generally northwest, but in detail they are sinuous and segments of the folds trend from west to north; their amplitudes range from about 20 to 120 feet. Two synclinal crossfolds were mapped in detail by determining altitudes or marker beds with telescopic alidade or hand level. These folds are shown on plate 1 and are called the Temple Mountain syncline and the Flat Top syncline.

The axis of the Temple Mountain syncline trends northwest under the Calyx Bench, west under Temple Mountain, and back to northwest west of Temple Mountain (pl. 1). The fold can be traced about 2 miles southeast from Temple Mountain, and it is inferred to extend about 1 mile west from Temple Mountain. The inference is based on the probable structure of the area before faulting, as shown in figure 7. (The structure was restored by assuming a normal dip-slip movement on the faults and projecting structure contours across downfaulted areas.)

The Temple Mountain syncline has noticeably deflected the regional strike of rocks near Temple Mountain. As shown by structure contours, the rocks of the Calyx Bench, on the south flank of the fold, strike about N. 30° E.; the rocks on the north flank of the fold strike N. 55°-60° E. (pl. 1).

The Flat Top syncline can be traced about 3½ miles through the northwest part of the district near Flat Top. North of Flat Top the fold is nearly straight and trends north-northwest; east of Flat Top the fold is sinuous but on an average trends northwest. Two small

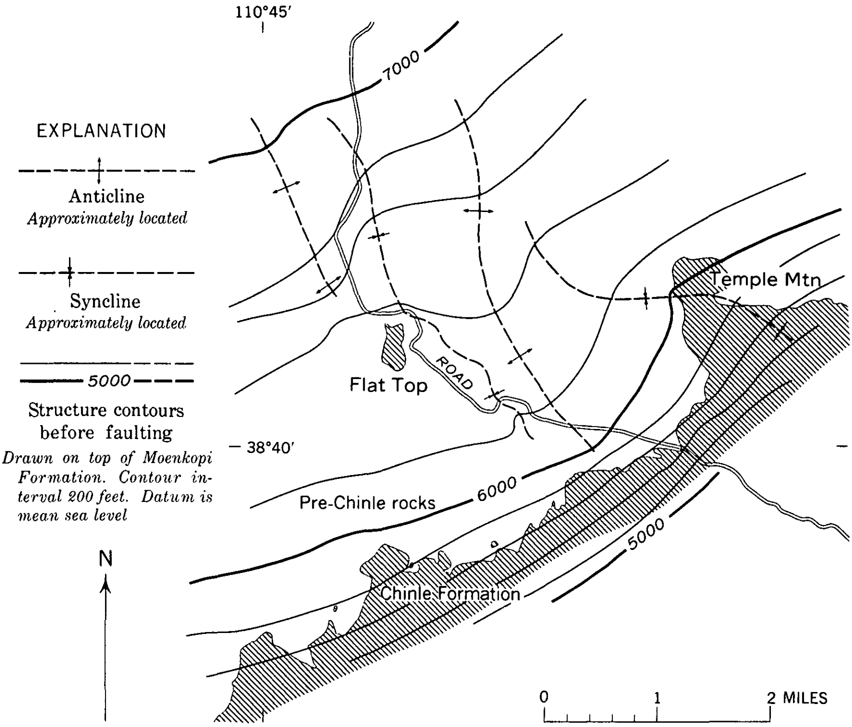

FIGURE 7.—Generalized reconstruction showing structure of part of the Temple Mountain district before faulting.

collapse structures are exposed along the trace of the axis of the fold (pl. 1).

The folds at Flat Top and Temple Mountain are two of an en echelon set that trends generally west-northwest toward a broad curve or regional bend in the main axis of the San Rafael anticline. The pattern of the folds is more apparent on the generalized structural reconstruction (fig. 7) than it is on the geologic map of the district (pl. 1).

The crossfolds probably formed normal to compressive forces that originated near the regional bend in the axis of the San Rafael anticline.

FAULTS

The major faults of the Temple Mountain district strike east and dip steeply north. Some of the major faults locally deviate in strike to west-northwest, and subsidiary faults, of small displacement, strike east-northeast and north-northwest. The faults do not appear to be influenced by folds of the district; they seem to cut indiscriminantly across the folds.

The major faults are high-angle dip-slip gravity faults, that define a series of horsts and grabens. The amount of displacement is as much as 200 feet toward the centers of the larger faults. Fault zones composed of several subparallel en echelon faults show distributive displacement; as displacement decreases on one fault it is taken up by a nearby parallel fault. Distributive displacement is illustrated by faults in the area between the Camp Bird 12 and North Mesa groups of mines (pl. 1).

West of the Camp Bird 12 group of mines, short high-angle faults that strike east-northeast join longer faults that strike east or west-northwest. The east-northeast faults have vertical displacements of 20 feet or less and probably formed at about the same time as the east-striking faults.

Faults of a north-northwest set have vertical displacements of less than 12 feet as well as horizontal displacements of as much as a few feet. They were observed only in some of the mine workings on the Calyx Bench. However, they may be more widespread but inconspicuous because of their small displacements. In the Vanadium King 1 mine they are spatially associated with faults striking west-northwest, but in general their relation to the other faults is uncertain.

The faults cut across the crossfolded rocks of the district and are believed to be younger than the crossfolds. Faults displace the Flat Top syncline at two places: east of Flat Top part of the syncline is downdropped by faults, and north of Flat Top the dip of rocks in two adjacent segments on the west flank of the fold are changed differentially by hinge-type movement of crosscutting faults (pl. 1). Although both relations could have resulted from the folding of faulted rocks, it seems much more likely that the faults are younger than the folds. No horizontal displacement of the trace of the synclinal axial planes by faults was observed. This absence of noticeable displacement probably is due to the dominant dip-slip component on the faults and a steep dip of the axial planes of the folds. Indirect evidence, discussed in more detail in following sections, supports the idea that the faults are younger than the crossfolds. Briefly, it is argued in later parts of the report that the Temple Mountain mineral belt is alined with the N. 30° E. strike produced by crossfolding, and so it is inferred that the ore deposition was later than the crossfolding. The ore deposits in turn are displaced by faults, which are, therefore, probably younger than the folds.

COLLAPSE STRUCTURES

Collapse structures are common in the gently dipping rocks that form most of the Colorado Plateau. They are not all the same type or of the same origin but include structures formed by volcanism, solution and collapse, and probably several other mechanisms. Some collapse structures appear to be syngenetic; others are epigenetic. Syngenetic collapse structures, which formed nearly at the same time as the enclosing sediments, are common in the Carmel, Entrada, and Bluff Formations of the Colorado Plateau; collapses of this type in the Laguna area have been described by Hilpert and Moench (1960, p. 441–42). Epigenetic collapses are probably much less common. They include solution-collapse structures of large vertical extent found in the Lisbon Valley area (Puffett and others, 1957). The collapses of the Temple Mountain district are also believed to be epigenetic and to have formed at least in part by solution and collapse; they are in part localized by crossfolds and probably formed during the folding of the San Rafael anticline.

Five collapse structures are exposed in the district (pl. 1). They consist of cores of strongly altered and downthrown rocks surrounded by an oval sag area in which the rocks are less altered and dip in toward the core. In places the core is mainly downwarped, but elsewhere it is downdropped along nearly vertical ring faults; at depth all collapse cores probably are bounded by faults. Exclusive of the gently dipping sag areas, the collapses range from about 100 to 2,500 feet across and have a maximum known vertical extent of about 800 feet. The rocks within the structures have subsided as much as 400 feet from their original position.

The rocks in and near the collapse structures are variably altered; as described on pages 110–115 and 117–118, alteration in and near the collapses consisted of removal of carbonates and petroleum, argillization, dolomitization, and ferrugination. The effects of the alteration extend for varying distances into the rocks in the sag areas. The extent of the alteration was probably partly controlled by the permeability of the rocks. Alteration extends for maximum distances of tens of feet in the siltstone-rich Moenkopi Formation, but extends out hundreds of feet in the sandstone- and mudstone-bearing Church Rock Member of the Chinle Formation and in the Wingate Sandstone.

TEMPLE MOUNTAIN COLLAPSE STRUCTURE

The Temple Mountain collapse structure is the largest and most complex collapse of the district. It is apparently a composite structure consisting of two major downfaulted masses, both of which are enclosed in a large sag area elongated along the west part of the Temple Mountain syncline (pl. 1). If the rocks of the sag area are included, the collapse is about 3,000 feet long and 1,500 feet wide. For descriptive purposes the two major downfaulted masses are called the East and West collapse structures (map of collapse area, pl. 1). The collapses are separated on the surface by the narrow ridge that joins North and South Temple Mountains. Data on subsurface relations suggest that the East and West collapses are structurally as well as topographically separate, and that both are bounded by nearly vertical ring faults. High-angle normal faults which strike about west-northwest and have small displacements are exposed east and west of the collapse but probably do not extend into it.

The Temple Mountain collapse structure has been described in several reports. Hess (1922) discussed it mainly as a body of highly altered rocks. B. N. Webber (written commun., 1944), recognized the collapse as a structural feature and compared it with "mineralization stoping pipes" described by Locke (1926). More recently it has been mapped and described by I. J. Witkind and others (written commun., 1954), by Keys and White (1956), and by Kerr and others (1955, 1957); Keys and White regarded the collapse as a single structure rather than as a complex structure composed of two main elements.

Small uranium deposits are found in the collapse; some are exposed on the surface, and a mineralized zone near the basal Moenkopi contact has been found by drilling (Keys and White, 1956, p. 295).

ROCKS

The rocks in both the East and West collapse structures are those of the Moenkopi, Chinle, and Wingate Formations. Drilling indicates that the collapses generally bottom on the Coconino and that the Kaibab is absent or is very thin throughout the collapse area (section *C–C′*, pl. 1). Lithologic features diagnostic of rocks of the Moenkopi, Chinle, and Wingate Formations allow ready identification of relatively undeformed and unaltered rocks within the collapse. Relatively undeformed Moenkopi, Moss Back, or Wingate sandstones may be recognized respectively by very fine crossbedding, pebble content, and large-scale crossbedding. Intense alteration and deformation, however, have obliterated the characteristic lithologic features of many of the component blocks, whose identities are therefore obscure or undeterminable. In general, the East collapse structure near the surface is largely Wingate Sandstone, the east part of the West collapse structure near the surface is also largely Wingate, and the west part of the West collapse structure near the surface is largely sandstone of the Chinle Formation. Some tentative identification of other component blocks are shown on the map of the collapse area on plate 1.

Limestone, dolomite, and calcite-cemented sandstone, although common in stratigraphically equivalent rocks outside the collapse, are rare within the collapse. Their scarcity is believed due to either epigenetic solution or, in the Kaibab Limestone, to nondeposition or erosion. The calcareous rocks of the Moenkopi are of uniform thickness in the district; beds of limestone or dolomite in the Moenkopi total about 75 feet in thickness. This fact, in addition to the absence of carbonates in the East and West collapses and the scarcity of calcareous cements in all rocks in and near the collapses, indicates that the carbonates were removed from the collapse structures, presumably by solution. On the other hand, the Kaibab shows considerable local variation in thickness and is known to be locally absent elsewhere in the San Rafael Swell (Gilluly, 1929, p. 82); these two factors suggest that absence is due to nondeposition or erosion. This suggestion is borne out by subsurface relations revealed in drill holes V–11 and V–7 (section *C–C′*, pl. 1). The Kaibab Limestone is very thin in V–11 and is absent in V–7, but the overlying Moenkopi in both drill holes is calcareous and is apparently undisturbed; therefore, the thinness and absence of the Kaibab near these drill holes is probably not due to solution. A nondeposition hypothesis is perhaps borne out by the structure of the Coconino Sandstone under the collapse. Section *A–A′* on plate 1 shows that the Coconino does not reflect the sag of the upper rocks but is, in fact, slightly higher than normal under the collapse; this "high" is probably a buried topographic feature in the upper part of the Coconino. (The more pronounced "high" on section *C–C′*, pl. 1, is exaggerated by the change in directon of the line of section.)

STRUCTURE

The East and West collapses are partly bounded by high-angle ring faults, which extend downward to at least the top of the Coconino Sandstone of Permian age. The faults separate the highly altered and fractured or contorted rocks of the cores of the collapses from the less altered, downwarped rocks of the large sag area in which both collapses are located. Ring faults that are subparallel to the boundary fault on the west and north sides of the West collapse cut the downwarped rocks adjacent to the collapse contact, and three small collapses are localized along or very near the northernmost of these subsidiary faults (map of collapse area, pl. 1).

The East collapse is separated from the West collapse on the surface by a septum of downwarped, but not downfaulted, Wingate Sandstone. Data from drill hole V–5 indicate that this septum continues in the subsurface and separates the collapses as shown on section *C–C′* (pl. 1). The hole was drilled in the septum adjacent to the northeast contact of the West collapse; it went through a normal little-deformed sequence down to about 710 feet, through both breccias and little-deformed rocks between 710 and 795 feet, and reentered little-deformed rocks, which were present to the bottom of the hole at 848 feet. These relations are interpreted to mean that the septum is bounded on the west by a nearly vertical fault that flares outward near the stratigraphic position of the Sinbad Limestone Member, but there returns to its projected vertical position. It is, of course, possible that the East and West collapses connect along another section line; but if they were continuous through a wide area, then the septum of Wingate Sandstone that divides the collapses on the surface would probably also be downdropped along faults. The nearly vertical fault that bounds the west end of the West collapse is well exposed in prospects. Like the fault cut by V–5, the west boundary fault is inferred to flare outward near the stratigraphic position of the Sinbad Limestone Member of the Moenkopi Formation (drill hole V–11, section *C–C′*, pl. 1).

The west boundary of the East collapse structure is a nearly vertical ring fault like those that form most of the boundary of the West collapse. The east boundary is in part covered by colluvium. On the basis of data from drill hole V–7 (section *C–C′*, pl. 1), it is inferred to be a curving fault dipping into the collapse. The undeformed rock cut at about 445 feet in the drill hole may, however, be a remnant in the collapse, and the east boundary of the East collapse may also be a nearly vertical fault.

Exposures and subsurface data suggest that the West collapse is itself a composite structure consisting of two main collapse elements separated by a high-angle fault (near drill hole V–3, map of collapse area and section *C–C′*, pl. 1). Just west of drill hole V–3, the contacts of the highly altered core of the collapse structure are gradational and the Moss Back Member can be traced from the sag area through the core of the collapse. Farther west and to the east of the drill hole, the contacts of the core of the collapse consist of nearly vertical faults. The vertical displacement of the base of the Moss Back Member on the postulated nearly vertical fault separating the main collapse elements is about 380 feet (section *C–C′*, pl. 1). As recognized by E. M. Shoemaker and W. L. Newman (written commun., 1952), the structure of the west part of the West collapse is like a trapdoor hinged at the place where the Moss Back Member can be traced across the collapse structure.

Some of the rocks in the East and West collapses are only slightly deformed; others show complex brecciation and flow structures (Keys and White, 1956, pls. 6*C*, 7*A*). Bedding is recognizable in many but not all of the collapsed rocks. High-angle fractures and faults of small displacement are characteristic of sandstones that still have bedding structures. A structureless aspect is typical of sandstones lacking bedding, and these unbedded rocks are interpreted to have been decemented and to have flowed into place. Fractured bedded sandstone and structureless sandstone are both exposed in the large mass of Wingate Sandstone that forms the east part of the West collapse; east of a conspicuous curving fault (map of collapse area, pl. 1), the sandstone is bedded and is similar to the Wingate Sandstone outside the collapse; west of the fault the sandstone is largely structureless.

The small-scale high-angle fractures and faults characteristic of the bedded sandstones in the cores of the collapses are also found in the downwarped sandstones adjacent to the cores. The high-angle fractures have diverse strikes and are traceable only for a few feet; displacement rarely exceeds 1 inch. They formed later than the introduction of at least some of the petroleum but earlier than some alteration. Typical time relations of these fractures to petroliferous rocks are shown in figure 8. The core on the left shows displaced petroliferous zones in Wingate Sandstone; the core on the right shows a fractured petroliferous sandstone of the Moss Back. In the Moss Back core the fractures have localized subsequent alteration and, as in most of the small-scale high-angle fractures, are healed with alteration minerals. Small-scale high-angle fractures also localized ore minerals in a small area near the southwest side of the West collapse.

Small-scale low-angle fractures are found in the sag area surrounding the collapse structure. The strike of the low-angle fractures almost parallels the strike of the beds, but the dips of fractures are in opposite directions to those of the beds. The orientation of the fractures, relative to that of the beds, suggests that the fractures formed because of the slippage of beds during downwarping, perhaps by the mechanism shown diagrammatically in figure 9. The low-angle fractures in the sag area surrounding the collapse are healed with alteration minerals, and they have localized ore minerals in the Vanadium

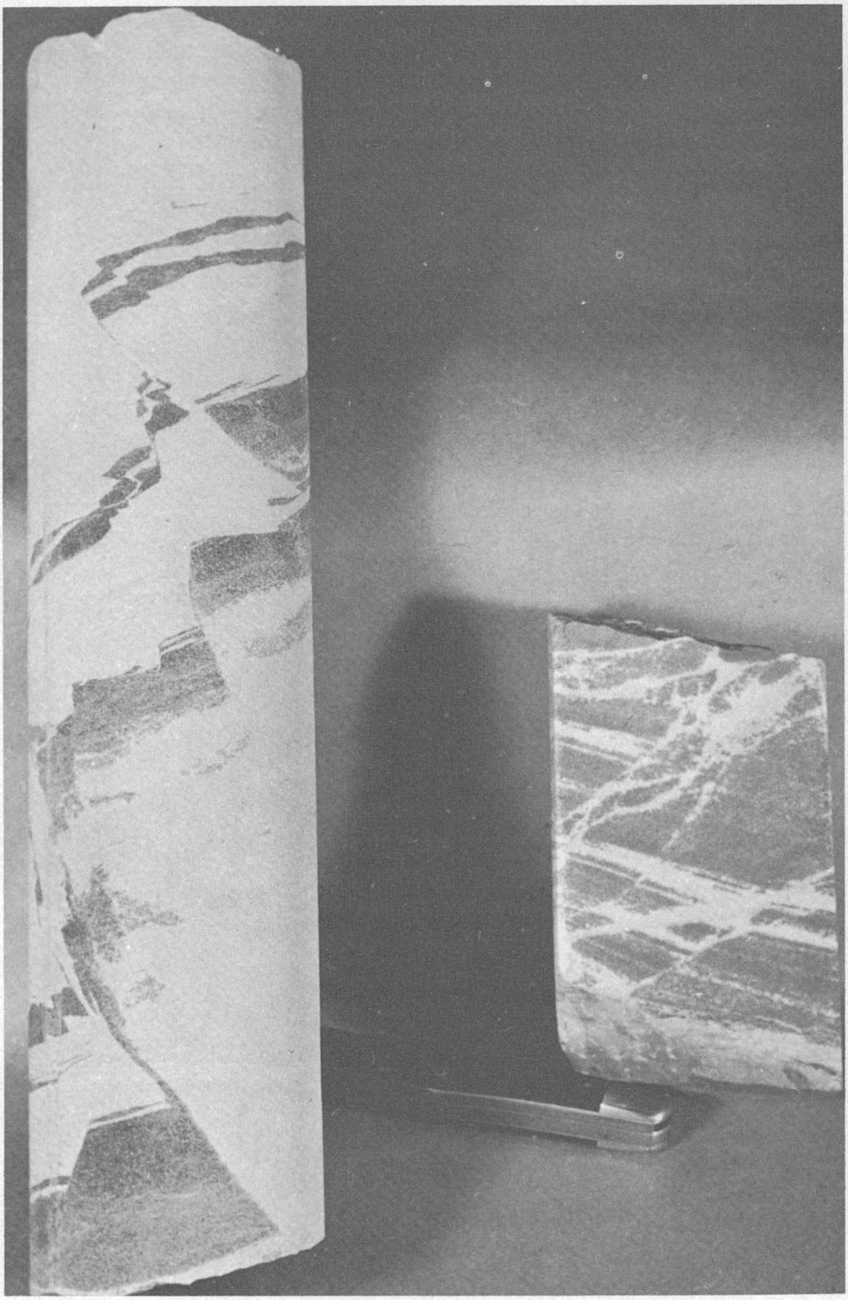

FIGURE 8.—Fractured and altered petroliferous sandstones, Temple Mountain collapse structure. Dark areas are petroleum stained. Wingate(?) Sandstone on left; sandstone of the Moss Back on right.

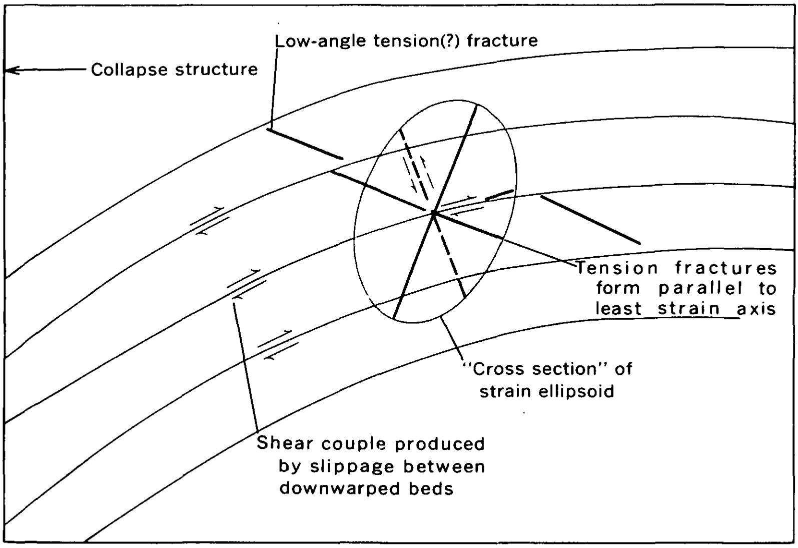

FIGURE 9.—Possible mode of origin of low-angle fractures in downwarped bedded sedimentary rocks near the Temple Mountain collapse structure.

King 5 mine (Moss Back Member) and in the Young prospect (Church Rock Member)—locations shown in figure 3.

Clastic dikes are a conspicuous small-scale feature of fractured rocks in and adjacent to the East and West collapses, and irregular clastic masses intrude the Wingate Sandstone east of the West collapse. The dikes are generally ½–2 inches across and are filled with petroliferous sandstone. (Clastic dikes are shown on plate 6*B*, Keys and White, 1956.) The irregular clastic masses are as much as 10 feet across. The dikes and irregular masses probably resulted from dilatant movement of water- or oil-saturated sands, formed by decementation of sandstones, into fractures and irregular voids caused by collapsing.

OTHER COLLAPSE STRUCTURES

The four other collapse structures of the district (pl. 1) are smaller, involve fewer rock units, and are less complex than the Temple Mountain collapse. All four are in the Moenkopi Formation, but three contain downfaulted rocks of the Chinle Formation.

One collapse is exposed 4,500 feet west of Temple Mountain on the southwest flank of the inferred projection of the Temple Mountain syncline (pl. 1). The highly altered core of the collapse is only about 100 feet across, and it consists of downfolded strata of the Moenkopi Formation. One hole (V–9) was drilled in the collapse to a depth of 317 feet; it was described by Keys and White (1956, p. 290–93). In this hole the collapse bottoms on the Coconino Sandstone at 300 feet. Brecciation was found in two zones: one from 163 to 223 feet and the other from 275 to 300 feet; this suggests that the downwarped type of collapse exposed on the surface extends downward into a collapse at least partly bounded by faults. Mineralized rock was also cut by the drill hole. Pyrite is abundant throughout the core; galena was found and anomalous radioactivity (319 counts per second) was recorded in a zone just above the Coconino contact.

Two collapses are exposed east of Flat Top (pl. 1). Both are composed largely of highly altered, downwarped rocks of the Moenkopi Formation within large saucer-shaped depressions, and both are on the axis of the Flat Top syncline. The eastern collapse, a mile southeast of Flat Top, is 550 feet long and extends north, roughly parallel to the axis of the syncline. To the north the axis of the syncline swings abruptly west, and minor effects of bleaching (not shown on pl. 1), extending from the collapse, swing with the fold axis. Two pluglike masses of conglomeratic sandstone of the Moss Back, which have subsided 400 feet, are exposed in the west part of the collapse; these masses and the adjacent rocks are radioactive (Jess Abernathy, oral commun., 1957). The western collapse is 3,000 feet east of Flat Top. It is 400 feet long and contains a pluglike mass of sandstone, which was derived from the Moss Back Member of the Chinle Formation and has subsided 300 feet.

The fourth collapse structure, west of Flat Top (pl. 1), is similar to the Temple Mountain collapse in having two surface expressions and in consisting largely of downfaulted, rather than downwarped, rocks. The blocks of the collapses are in an area of alteration 750 feet long and 300 feet wide, which in turn is in a gently downwarped oval area 2,000 feet long by 1,000 feet wide. The major axis of the oval area trends east. The west block is composed partly of conglomeratic sandstone of the Moss Back downdropped 280 feet. The east block is composed largely of sandstone, possibly derived from sandstone-rich parts of the Moss Back Member of the Chinle Formation. The west block contains a small amount of uraniferous asphaltite.

ORIGIN OF THE COLLAPSE STRUCTURES

Several modes of origin have been proposed for the collapse structures of the Temple Mountain district and somewhat similar structures elsewhere; they include volcanic explosions and subsequent subsidence of pluglike or broken masses of rock (Gabelman, 1957), solution and subsequent subsidence into the voids thus formed (Keys and White, 1956), penecontemporaneous subsidence of sand into water-saturated mud (Schlee, 1959), and landslides. In addition, Phoenix (1958) proposed that small sandstone pipes found in the Carmel Formation fill voids formed penecontemporaneously by water escaping under hydrostatic pressure from beds at the base of the pipes. Certain of these modes of origin can probably be disregarded because of geologic relations of the collapses of the Temple Mountain district; but one mode, that of solution and subsequent collapse, seems at least partly valid as an explanation of the origin of the collapse structures. An explosive volcanic origin seems unlikely because of the lack of exotic rocks that would be derived from deeply buried units and because of the apparent bottoming of collapses on nearly undeformed Coconino Sandstone. In general, a penecontemporaneous origin seems improbable because of the large stratigraphic interval involved, particularly in the Temple Mountain collapse, and because of the spatial association of collapses with crossfolds which probably formed during folding of the San Rafael anticline. Small-scale features such as brecciation of petroliferous rocks also are difficult to explain by a penecontemporaeous origin. A landslide origin is not consistent with the nearly vertical boundary faults of the collapses, their continuity into the subsurface, and other features.

In contrast, subsidence of rocks into solution-formed cavities seems likely to be at least a contributory cause of the collapse structures. As noted earlier, carbonate rocks and calcite cements are scarce in the collapse structures, partly owing, probably, to solution. Particularly in the lower part of the Moenkopi Formation the virtual absence of carbonates probably was caused by solution, and the voids that resulted were filled by brecciated masses of the younger rocks.

The removal of carbonates by solution is not, however, the whole answer to the problem. As recognized by Keys and White (1956), Gabelman (1957), and Kerr and others (1955; 1957), the amount of carbonates removed does not nearly account for the amount of subsidence observed. This "room problem" can possibly be solved in several ways. Keys and White (1956, p. 294) proposed that: "If the limestones were dissolved for a considerable distance outward from the collapse center, the unconsolidated sediments might have flowed into the space thus provided." The outward flaring of collapses into carbonate-rich zones is borne out to some extent by drill holes V–5 and V–11 in the West collapse of the Temple Mountain collapse structure (section *C–C′*, pl. 1) but it does not appear to provide enough additional volume to the collapse to account for several hundred feet of subsidence.

A second possibility is that additional room was provided by the solution of some siliceous rocks. The solutions that deposited dolomite, particularly in the Wingate Sandstone, apparently were undersaturated with silica and consequently dissolved the silica from detrital grains of chert, feldspar, and quartz. The solutions that dissolved carbonates in the collapse structures may have also been undersaturated with silica and dissolved some quartz and other detrital silicates in the collapse structures themselves.

Still a third possibility is that some of the decemented material in suspension moved outward into the surrounding rocks. The presence of numerous small sandstone dikes suggests that this did happen on a small scale, but, in general, it seems that the space problem has not been completely solved.

The range in size and in amount of displacement of the collapses seems to fit in a solution-collapse hypothesis, and the collapse structures seem to constitute what can be termed an "evolutionary group." The earliest stage in development may be represented by the small collapse west of Temple Mountain. In this collapse it may be inferred that solution of the lower part of the Moenkopi (and the Kaibab if it were present) had started and had progressed sufficiently so that a small void was formed. This void was filled with brecciated rocks of the lower part of the Moenkopi as shown by core from drill hole V–9. The void was relatively small, however, and so the upper part of the Moenkopi was not faulted but merely sagged into it. The next stage is represented by the collapses east of Flat Top, in which small pluglike masses of Chinle were dropped into the altered downwarped Moenkopi. The final stage is represented by the Temple Mountain collapse, where extensive solution in the Moenkopi produced large voids into which large masses of the younger rocks dropped on circular faults.

If solution can be accepted as a contributory cause of the collapse structures, then it seems valid to speculate briefly on the localization of solution. The roughly cylindrical (crudely oval in plan) shape of the collapses suggests effective point sources at depth for the solutions that dissolved the carbonates and perhaps also other rocks. Small pipelike conduits could underlie the collapses and not have been intersected in the widely spaced vertical drill holes; however, point or short linear sources might also result at the intersection of different geologic features. In turn, this suggests multiple geologic controls for the collapses. Controls that probably contributed to localization of four of the collapses are the Temple Mountain and Flat Top synclines. This is evident from the proximity of the four collapses to the axes of these folds. Other controls could have been buried topographic or structural highs and fault or fracture zones. In the Temple Mountain collapse, the void-forming solutions may have been concentrated at the intersection of the Temple Mountain syncline and a preexisting local high in the Coconino Sandstone. Faults and fractures in the deeper rocks may also have contributed to formation of the collapses, but no direct evidence of their presence is known.

GEOLOGIC HISTORY

Most of the rocks of the Temple Mountain district were deposited under shallow-water marine or continental conditions. The oldest exposed formation, the Coconino Sandstone, possibly reflects near-shoreline, beach conditions which gave way to a shallow marine environment during Kaibab time. A period of uplift followed in which the Kaibab was locally channeled, possibly by northwest-flowing streams that deposited the basal conglomerate of the Moenkopi Formation. During most of Moenkopi time, the environment may have been that of a tidal flat, changing to marine during an eastward transgression of the sea in Sinbad time. The shallow waters withdrew completely after the deposition of the Moenkopi, and uplift and local erosion preceded the deposition of the Chinle Formation.

The withdrawal of the sea after deposition of the Moenkopi marks the beginning of a period of continental deposition, which lasted from Late Triassic into Jurassic (Carmel) time. The oldest of the continental formations, the Chinle Formation, was deposited by wide-ranging river systems. The sandstones and conglomerates of the Chinle represent the channel deposits; the siltstones and mudstones probably represent flood-plain or lake deposits. No apparent erosional break separates the Chinle from the Wingate Sandstone, and the change in character of sedimentation may have resulted from an increasingly arid climate.

The rocks representing the later geologic history of the district have been eroded; thus, this history is more speculative. Deposition of sedimentary rocks under marine or continental conditions probably continued with only minor cessations into Late Cretaceous time. In the early Tertiary, conditions changed as the result of the Laramide orogeny, and the San Rafael anticline was formed, thus initiating a cycle of erosion. (The most probable date of formation of the anticlines—or monoclines—of the western Colorado Plateau is Paleocene time (Hunt, 1956, p. 73–76; Spieker, 1954, p. 13).) Probably late in the folding of the anticline, its axis began to bend and the crosswarps formed as the result of forces acting about parallel to the major fold axis. Solutions accumulating in the upper part of the Coconino in the anticlinal structure locally were concentrated and "stoped" their way upward through the fine-grained Moenkopi Formation, thus forming the collapses. As pointed out in later sections of this report, these solutions are probably the ones that deposited the ore in the Temple Mountain district. Still later the rocks were broken by gravity faults, features that in addition to rock type have strongly influenced the work of erosion, the dominant geologic process of recent times.

URANIUM DEPOSITS

The uranium deposits of the Temple Mountain district occur in several formations and in collapse structures that cut across formational boundaries. The hosts of the deposits are petroliferous sandstones principally in the Moss Back Member of the Chinle Formation and subordinately in the Coconino Sandstone, the lower part of the Moenkopi Formation, the Church Rock Member of the Chinle Formation, and the Wingate Sandstone. Except for a few small discordant ore bodies in and near collapse structures, the ore bodies are of peneconcordant type (Finch, 1959).

The largest ore bodies are in the Moss Back Member of the Chinle Formation and occur in a northeast trending belt near Temple Mountain. Small ore bodies in the Moss Back are found updip from the belt at Temple Mountain and at Flat Top. The major ore bodies of the belt are rolls elongated in a northwest direction. The direction of elongation of rolls and associated tabular bodies at least locally parallels the trend of sedimentary structures, but near Temple Mountain it is perhaps more generally parallel to the dip of the enclosing strata.

In addition to uranium and vanadium, ore bodies and nearby altered rocks contain abnormal concentrations of selenium, arsenic, chromium, and a few other elements. The ores are generally unoxidized, and the ore components occur in low-valent states as a native element (arsenic), sulfides, selenides, oxides, and oxysalts accompanying a black carbonaceous substance which has commonly been termed "asphaltite." Asphaltite is the most abundant component of the ore. Along with sparse metallic minerals it fills pores and replaces, in varying degree detrital grains, mineral cements, and coaly materials of the host rocks.

Many of the rocks of the district are noticeably altered; this alteration is particularly conspicuous near the collapse structures and near sharp boundaries of ore deposits. Rocks near the collapse structures generally have been bleached, and large concentrations of dolomite and siderite have formed respectively in the Wingate Sandstone and in the Church Rock Member of the Chinle Formation. Near the ore deposits, calcite cements and petroleum were removed, and chromium-bearing silicates and dolomite were formed during alteration. The ore-bearing zones are bordered on at least one side by strongly altered zones nearly devoid of petroleum and calcite cement.

DISTRIBUTION AND GENERAL CHARACTER OF THE DEPOSITS

DEPOSITS IN THE MOSS BACK MEMBER OF THE CHINLE FORMATION

Uranium deposits have been mined in the Moss Back Member of the Chinle Formation near Temple Mountain and on Flat Top. No major uranium deposits have been found in these strata in the other parts of the district; but fossil logs and concentrations of fine detrital carbonaceous material in the Moss Back locally are uraniferous, and a thin zone near the contact of the Monitor Butte and Moss Back is slightly radioactive at most exposures in the district.

The Temple Mountain area contains most of the deposits, and most of these are on the Calyx Bench in the Temple Mountain mineral belt (fig. 12), an area of mineralized rock first delineated by U.S. Atomic Energy Commission drilling (Keys and White, 1956, p. 295–297). The belt extends 9,000 feet north-northeast from the Black Beauty mine in the south part of the area to the Vanadium King 1 mine, beyond which any possible continuation has been eroded. Its greatest width is 2,300 feet; its average, less than 2,000 feet. Ore is not known to exist downdip from the belt, but small ore bodies have been found on the updip side toward Temple Mountain.

The position of the belt can be inferred from the extent of the mine workings (pl. 3). The ore bodies in the belt, as indicated by the general outlines of mine workings on plate 3, are oriented about perpendicular to the trend of the mineral belt; in this respect, the Temple Mountain belt resembles the Uravan mineral belt in southwestern Colorado (Fischer and Hilpert, 1952, p. 5, pl. 2), which is, however, traceable for tens of miles and therefore much larger.

At Flat Top, uranium deposits crop out on the periphery of the entire mesa, but extensive drilling has shown that the larger deposits are in the north part.

Most ore deposits occur in a zone 10–40 feet above the base of the Moss Back Member. Locally, as at the North Mesa 2 and Vanadium King 5 mines, respectively, ore occurs in the lower 10 feet and uppermost part of the Moss Back. The vertical position of ore in most places coincides with that of the massive sandstone facies of the Moss Back. In several mines, ore occurs in two or more stratigraphic levels, and locally two or more ore bodies are stacked vertically. For example, two ore bodies are superposed just north of 119,400 N.–18,400 E. in the Calyx 8 mine (pl. 4).

The general stratigraphic position and the vertical range of ores within the Moss Back Member in the Temple Mountain district differ from the position and range of most other ore deposits in the Moss Back Member in other parts of the San Rafael Swell. In most other deposits, ore occurs in only one level, and this is generally within the basal 10 feet of the Moss Back Member.

Uranium deposits occur as both tabular and roll ore bodies in the Moss Back Member in the Temple Mountain district. The tabular bodies conform closely to bedding; most rolls are partly concordant, but in part they cut or roll sharply across the bedding. The rolls and tabular deposits grade into each other, but in most places an ore body can be classified as dominantly tabular or dominantly roll-like. The rolls of the district are similar to those described from other parts of the Colorado Plateau by Fischer (1942, p. 379–384), B. N. Webber (written commun., 1947), Shawe (1956), and Shawe, Archbold, and Simmons (1959, p. 408–414). Most rolls are elongate ore bodies having a general crescent- or C-shaped cross section. The shapes of rolls are complex and the cross-sectional shape can change continuously along the trend of the roll. The rolls are straight to sinuous in plan and locally double back on themselves forming approximate mirror-image rolls at about the same stratigraphic position.

Ore bodies 3, 4, 5, and 6 in the Calyx 8 mine (see index map, pl. 4) illustrate some of the variations in shape of the ore bodies of the district. Of these four ore bodies, two (3 and 6) can be classed as dominantly roll-like, and one (5), as dominantly tabular; one (4) grades from tabular to roll-like. Ore body 3 shows some of the typical variation in cross-sectional shape observable along the trend of most rolls; it is also typical in having, in cross section, one sharp contact and one gradational contact (fig. 10). Ore body 5, although largely tabular, also shows this latter characteristic (fig. 11). The ore thickens northwest along the main ore trend of 5, and the shape of the sharp or roll-like contact at the northeast edge of the ore body becomes more complex. Ore body 4 grades north from a large generally tabular body, through a gently curving roll, to a tight roll (fig. 11). Mirror-image relations are shown by ore body 6, which loops back on itself in plan (pl. 4) and thus forms two mirror-image C-rolls; mirror-image relations are possibly shown by ore bodies 3 and 4, which are at about the same stratigraphic position, present concave images toward each other, and are separated by only a small zone of barren rock near their south ends.

Individual ore bodies in the Temple Mountain mineral belt have yielded 1,000–20,000 tons of ore. The largest single ore body is that of the Calyx 12 mine; it has been followed for about 700 feet and has yielded 20,000 tons of ore. The larger ore bodies of the Calyx 8 mine have yielded 6,000–10,000 tons of ore. These ore bodies—2, 3, 4, and 6 (pl. 4)—are, at least partly, roll-like in form; ore bodies 2 and 3 are, respectively, 120 and 160 feet long; ore bodies 4 and 6 are both 360 feet long. The ore bodies average 40 feet in width and range from 2 to 15 feet in thickness. The largest tabular deposits in the belt, those of the North Mesa 2 and Calyx 9 mines, are 120 feet long, 70 feet wide, and as much as 12 feet thick.

The ore deposits at Temple Mountain, west of the mineral belt, and at Flat Top are smaller. Individual ore bodies contain only a few

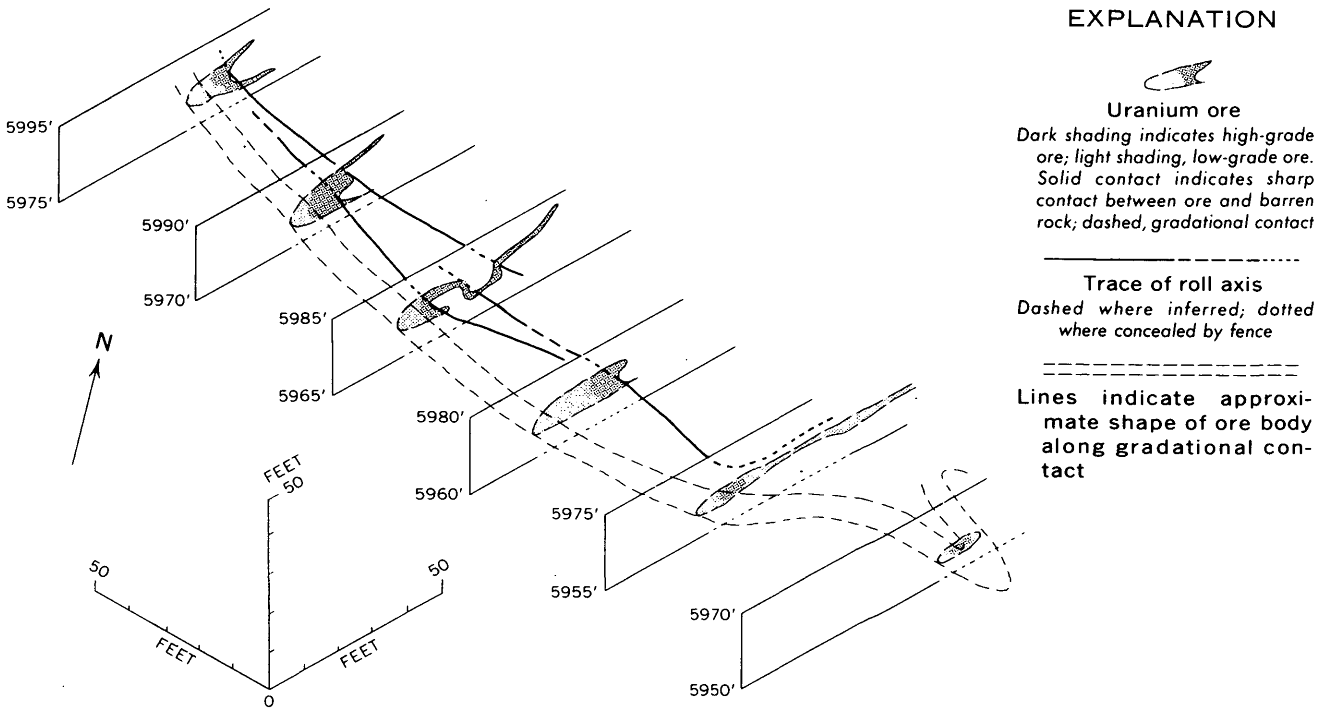

FIGURE 10.—Fence diagram of ore body 3, Calyx 8 mine, Temple Mountain district. Datum is approximately that established by Union Carbide Nuclear Co. Roll axis is shown on plate 4.

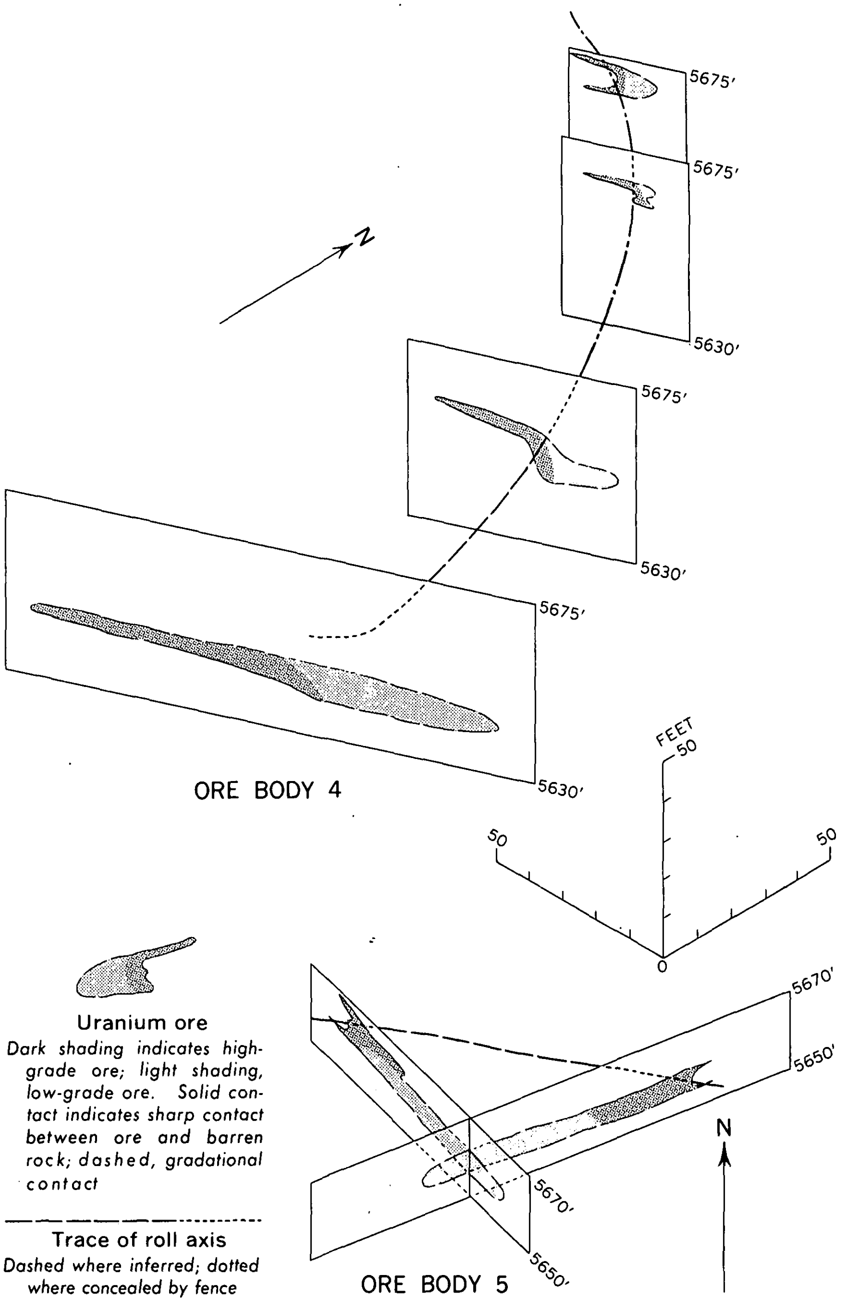

FIGURE 11.—Fence diagrams of ore bodies 4 and 5, Calyx 8 mine, Temple Mountain district. Datum is approximately that established by Union Carbide Nuclear Co. Roll axes are shown on plate 4.

hundred tons of ore; closely spaced ore bodies in the Vanadium King 5 mine on North Temple Mountain have yielded over 2,000 tons of ore.

DEPOSITS IN OTHER ROCK UNITS

Small uranium deposits have been found at Temple Mountain in the Church Rock Member of the Chinle Formation and in the Wingate Sandstone. Although production records are lacking, none of the deposits could have contained more than several hundred tons of ore. The uranium deposits in the Wingate on both North and South Temple Mountains are found through a considerable stratigraphic range. The larger of these small deposits are in the basal part of the Wingate at the Vagabond mine and at mine BI–9 (fig. 3), and in the upper part of the Wingate at the Eagles Nest mine and at the Migliaccio prospect (fig. 3). The larger deposits in the Church Rock Member are at the Vagabond mine and the Young prospect.

The deposits in the Wingate, like those of the Moss Back, are rolls or tabular bodies. The ore bodies in the Church Rock Member at the Vagabond mine are rolls, but at the Young prospect the ore occurs in a thin tabular seam along a fracture.

Abnormally uraniferous rocks are found locally in the Kaibab Limestone, the Sinbad Limestone Member of the Moenkopi Formation, and the Temple Mountain and Monitor Butte Members of the Chinle. Small uraniferous asphaltite nodules occur in the Sinbad Limestone Member 8,000 feet west of Temple Mountain and are reportedly found in a sandy facies of the Kaibab about 1 mile north of Temple Mountain (R. L. White, oral commun., 1956).

In addition to uranium minerals, single crystals or sparse aggregates of galena and copper sulfides are found in the Sinbad Limestone Member at three widely separated localities west of Temple Mountain. The wide distribution of these minerals and local anomalous radioactivity suggest that the Sinbad Limestone Member is slightly mineralized throughout much of the district.

DEPOSITS IN THE COLLAPSE STRUCTURES

Small deposits of uranium minerals or anomalous amounts of radioactivity are known from all the collapses except that due east of Flat Top (pl. 1). Most of the deposits in the collapse structures—including all the larger ones—are in the Temple Mountain collapse, where they are found at three places: (1) near the west end of the Flopover, (2) near the east contact of the east collapse, and (3) in a zone near the Moenkopi-Coconino contact at depth (as shown on section *C–C′*, pl. 1). At these places the ore occurs in nearly vertical pipes, in veins, and in roll-like masses, as well as in less regular forms in breccia zones.

The zone of mineralized rocks near the Coconino contact must be largely tabular, because ore or mineralized rocks are found near this horizon in 11 diamond-drill holes (V–1—V–10, and 2–31, map of collapse area, pl. 1). Nearly vertical masses of ore are inferred to occur in the zone, because some ore contacts in core from the vertical drill holes are subparallel to the holes.

Ores in breccias occur at the Fumerol mine and in prospect BI–6 (fig. 3); they illustrate the age relations between the introduction of petroleum and ore. Petroleum is inferred to have been introduced prior to brecciation, because blocks of petroliferous sandstone occur in a nonpetroliferous mudstone matrix. The ore, however, formed after brecciation. In prospect BI–6 (fig. 3), a contact between altered and unaltered rocks cuts across the breccia, through both blocks and matrix. The altered sandstones contain sulfides, native arsenic, and asphaltite; the unaltered contain only petroleum. In places the contact of alteration cuts through a sandstone block; the part of the block on the altered side contains asphaltite, which appears to grade into petroleum half an inch or less from the alteration contact.

Only a small amount of ore has been produced from deposits in the collapse structures. Slightly over 100 tons of ore has been produced from the Fumerol mine since 1948, and some ore probably was mined from prospects BI–5 and BI–6 (fig. 3) and other places during earlier mining activity.

LOCALIZATION AND CONTROLS OF ORE IN THE MOSS BACK MEMBER OF THE CHINLE FORMATION

The position, shape, and size of the uranium deposits correlate in varying degrees with several geologic features; this suggests multiple controls of mineralization. The spatial association of mineralized areas with collapse structures suggests a genetic relation between mineralization and collapses, a relation which is borne out by metal zoning and rock alteration, geologic aspects discussed later in the report. Structural control by folds is inferred from the orientation of the Temple Mountain mineral belt, which is subparallel to the local structure contours but is at a large angle to the local sedimentary trend. Lithologic control of ore is, however, also inferred because the major ore bodies occur in channel deposits of the massive sandstone unit of the Moss Back Member, and because most deposits, in detail, conform closely to lithologic features.

LARGE-SCALE CONTROLS

Several geologic features influenced the general position of the ore deposits. These features are called the large-scale ore controls and in terms of their relative importance in decreasing order, are (1) collapse structures, (2) folds, (3) lithology of the massive sandstone unit, and (4) major channel deposits of the massive sandstone unit. The collapse structures determined the most general location of deposits, the Flat Top and Temple Mountain areas; folds determined the orientation of the main belt of deposits at Temple Mountain; and lithology and channel deposits largely determined the places of uranium deposition in the Moss Back Member.

A relation to fold structures is suggested by the fact that the Temple Mountain mineral belt is subparallel to the strike of the rocks on the updip side of the monoclinal fold which underlies part of the San Rafael Reef, but cuts across the sedimentary trends. The belt is approximately between the 5,760- and 5,440-foot structure contours on the base of the Moss Back Member on the Calyx Bench (pl. 3), and if the south part of the belt is restored to its position before normal faulting, then all large ore bodies of the Temple Mountain area are between these contours (fig. 12). The local strike of beds near Temple Mountain conforms closely to the trend of the mineral belt and resulted from the formation of the Temple Mountain synclinal crossfold; thus, both the monocline and crossfold may have influenced uranium deposition.

Although the massive sandstone unit of the Moss Back Member generally makes up less than one-third of the member, it contains most of the ore deposits; this fact indicates that the lithologic character of the unit was an important ore control. Additional evidence of lithologic control of ore is the fact that lenticular sandstones, similar to the sandstones of the massive sandstone unit but scattered in the limestone-pebble conglomerate and platy sandstone facies, are locally ore bearing. The preference of uranium deposits for the massive sandstone unit is well shown in outcrops. On Flat Top, 13 of 19 ore outcrops are in this unit; and near Temple Mountain the unit contains ore bodies that crop out at the Vanadium King 1, Camp Bird 12 (pl. 6), and North Mesa 1 and 2 mines (section *C–C′*, pl. 5).

Why ore solutions mineralized the massive sandstone unit in preference to other rocks is not fully understood. The sandstones of this unit are typically less well cemented with calcite than are the rocks of the overlying and underlying units, and typically they are probably coarser grained and better sorted than sandstones of the other facies. These features suggest that the rocks of the massive sandstone facies were more porous and permeable than most other rocks. The massive sandstone facies is also typically more petroliferous than other facies, and this probably contributed to its selection as host rock; the petroliferous nature of the unit is also taken as indirect evidence for inherently greater porosity and permeability.

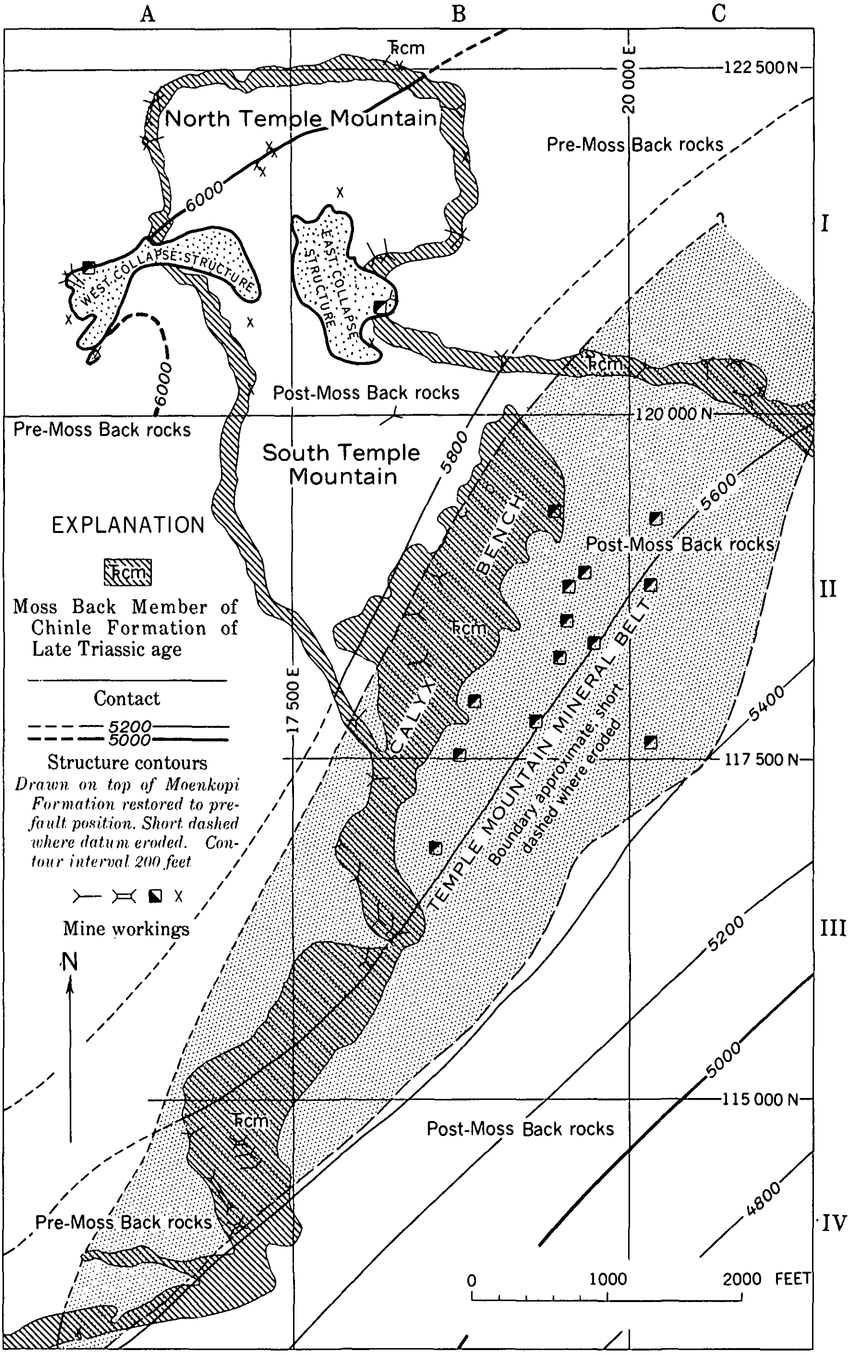

Figure 12.—Inferred structure of the Temple Mountain mineral belt before faulting.

The ore bodies on the Calyx Bench are in the part of the area underlain by the north-northwest-trending Temple Mountain paleochannel; the ore bodies in the Camp Bird 12 group are in the smaller, subparallel paleochannel exposed south of the Calyx Bench. The Moss Back Member in the area between the two channels, where it includes only a thin section of the massive sandstone unit, has been drilled with negative results (A. H. Anderson and R. D. Miller, written commun., 1952).

SMALL-SCALE CONTROLS

The shape and orientation of both roll and tabular ore bodies are, in part, controlled by the shape of sandstone lenses, the orientation of minor scours, by mudstone splits, and rarely, by joints and faults of small displacement.

Control of ore by shape of sandstone lenses is shown in several mines: in the Calyx 3 mine, detailed structure contouring of the top and bottom of the mineralized sandstone shows that the main ore body is in the thick part of a northwest-elongated sandstone lens (Baumgardner and Noble, written commun., 1957); a similar relation is found in the south part of the Big Heading, Calyx 8 mine (pl. 4), where northwest-trending roll ore body 3 is in the thicker part of a sandstone lens and parallels a scour cut into the sandstone a few feet east of the ore body. On Flat Top some ore bodies are confined to sandstone lenses in the massive sandstone facies, and in the North Mesa 2 mine the main ore body conforms in shape to its host rock, a lenticular conglomeratic sandstone (section *A–A′*, pl. 5).

Mudstone splits are perhaps the most obvious small-scale ore control. Presumably because of their lesser permeability, they had a confining effect on mineralizing solutions that is shown by the present distribution of ore. The ore bodies are found in sandstone lenses capped and floored with mudstone-rich rocks; where the confining mudstone layers thin, the ore may cross into other sandstone lenses.

Low-angle fracture zones control some primary (unoxidized) ore in deposits in the Moss Back on North Temple Mountain. Fracture-controlled ore occurs in the Vanadium King 5 mine (fig. 13) and possibly in the Camp Bird 7 mine. At the Vanadium King 5 mine the ore occurs as nodules and seams less than an inch thick along fractures; the fracture zones are followed in mining. The fractures generally cut the bedding at a small angle but in places curve into the bedding. In the Camp Bird 7 mine a 1-foot layer of ore cuts across the bedding of the sandstone at a small angle (fig. 14) and parallels what appear to be mineralized fractures in the sandstone below the ore.

Some primary ore on the Calyx Bench may also be controlled by low-angle fractures. According to P. H. Dobbs (oral commun.,

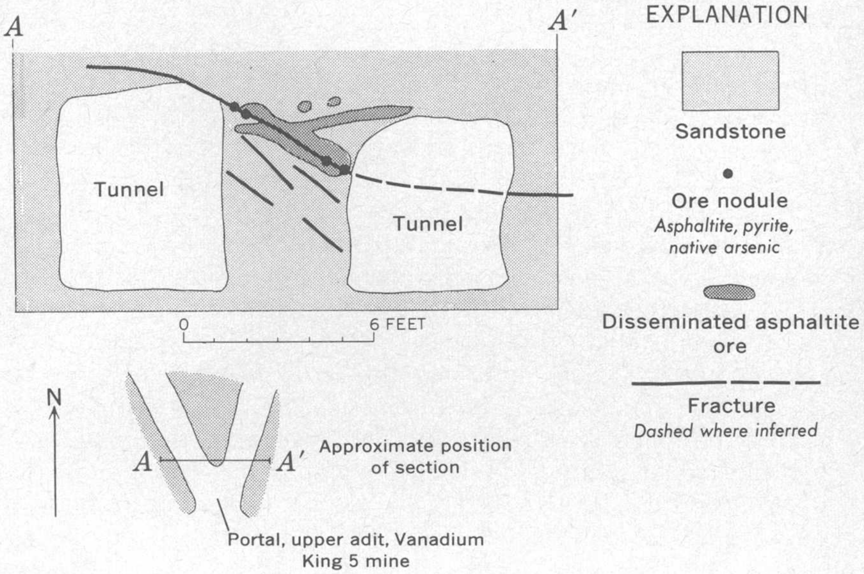

FIGURE 13.—Fracture-controlled ore, Vanadium King 5 mine.

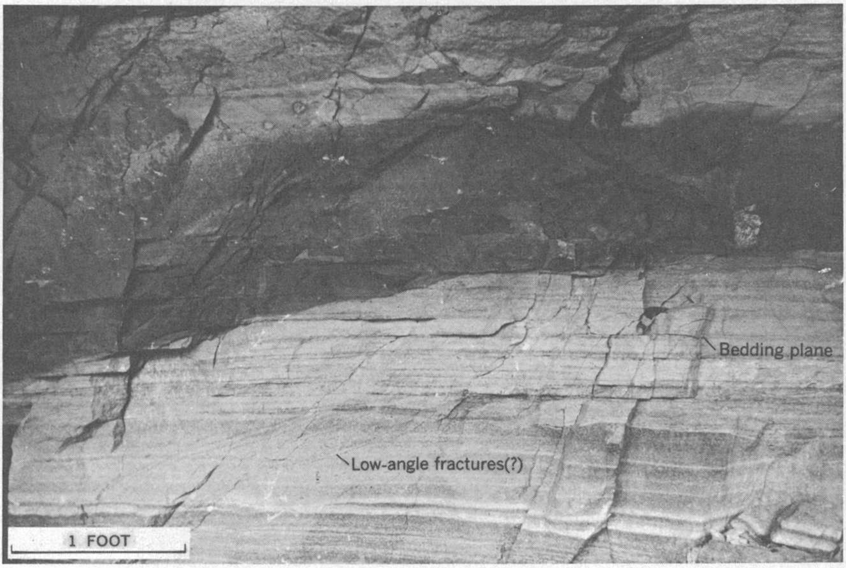

FIGURE 14.—Fracture-controlled(?) ore in the Moss Back Member of the Chinle Formation, at the Camp Bird 7 mine. Dark rock is asphaltite-uranium ore. Note sharp lower ore contact. See figure 40 for location.

1956), an ore zone in the Calyx 12 mine is probably on a low-angle fracture, and some ore in the Camp Bird 12 mine may be on bedding-plane fractures. Small-scale fractures, apparently confined to mudstone, localized asphaltite nodules adjacent to ore bodies in the Calyx 8 mine (fig. 15), on Flat Top, and probably at many other places in the district.

Minerals of high-valent uranium or vanadium coat walls of fractures in most mines. These minerals appear to be of recent supergene origin and are not commonly abundant enough to constitute ore.

It has also been proposed that high-angle normal faults controlled ore (Keys aand White, 1956, p. 296). The west- and west-northwest-striking normal faults, however, appear to displace primary ore bodies. The smaller north-northwest-striking faults also probably postdate ore; they are roughly parallel to some ore bodies and have been followed in mining, but detailed mapping in Calyx 8 shows that here at least they displace the ore and are not truly parallel but cross the ore trends at small angles.

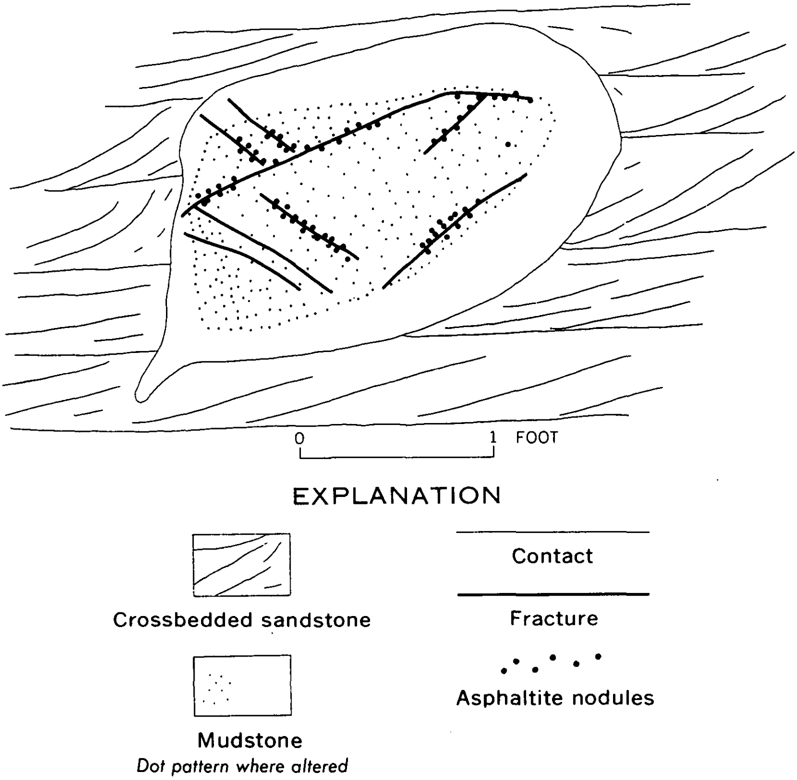

FIGURE 15.—Fracture-controlled distribution of asphaltite nodules in mudstone, Calyx 8 mine.

Although many ore bodies are obviously controlled by sedimentary structures, the dip or structural tilt of beds also possibly influenced the distributon of ore. In general, the long direction of ore bodies on the Calyx Bench coincides more closely with the southeast dip direction than it does with the direction of sedimentary trends (north-northwest). Without additional detailed information on sedimentary trends in all the mines, it is impossible to state whether there is a real or only seeming correlation of ore bodies with sedimentary trends. A tentative conclusion is that both sedimentary structures and dip direction locally contributed to the channeling of ore solutions, which resulted in ore bodies elongate in the northwest-southeast direction.

LOCALIZATION AND CONTROLS OF OTHER ORES

Both tabular deposits and rolls are found in the Wingate Sandstone on Temple Mountain. The tabular deposits are controlled by bedding, particularly by the flat bedding planes that truncate cross-bed sets. The rolls, however, have no obvious sedimentary or tectonic structural control. Although sharp roll boundaries have been considered by some as fracture controlled, complex shape and lack of correlation with visible fractures suggest a different control. The boundaries could have formed at interfaces between solutions that had different properties (Shawe, 1956). Fracture control, however, was observed in the Church Rock Member at the Young prospect; there, a thin asphaltite seam fills a low-angle fracture that is apparently typical of fractures found near the Temple Mountain collapse structure. Similar fractures locally controlled the bleaching of the originally red sandstones of the Church Rock near the collapse (fig. 16).

Pipes and nearly vertical plunging roll-like masses of ore found in the Temple Mountain collapse structure are locally controlled by the characteristic small-scale high-angle fractures of the collapse.

CHEMICAL COMPOSITION OF THE ORES AND THEIR ENRICHMENT RELATIVE TO BARREN ROCKS

Basically, the ore deposits are sandstones impregnated with asphaltite and small amounts of metallic minerals. The most abundant constituents of the sandstones are the common rock-forming elements—silicon, aluminum, and iron—and organic carbon. Uranium, vanadium, selenium, and arsenic are the rarer elements present in the largest concentrations in the ores. Selenium, uranium, and vanadium are also the elements most highly enriched in the ores relative to their concentrations in barren rocks.

The chemical composition, exclusive of carbon content, of the Temple Mountain ores is summarized in two tables. Table 3 lists

TABLE 3.—*Average chemical composition of uranium deposits in the Moss Back Member of the Chinle Formation, Temple Mountain area*

[M, major constituent (>10 percent); Nd, not determined. PMS and GS samples collected by U.S. Geol. Survey. Chemical analyses by E. J. Fennelly, H. H. Lipp, G. T. Burrow, and Claude Huffman, Jr. Spectrographic analyses by R. G. Havens, P. J. Dunton, and N. M. Conklin. All analyses reported as weighted geometric mean except No. 1—reported as weighted arithmetic mean by A. T. Miesch]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Chemical analyses															
U	0.10	0.18	0.14	0.18	0.15	0.37	0.22	0.25	0.19	0.14	0.25	0.28	0.26	0.17	0.36
V	.16	.30	.25	.31	.27	1.1	.39	.43	.59	.30	.56	.79	.82	.54	.67
Se	.00009	.012	.010	.016	.008	.0250	.0375	.0433	.0373	.0215	.0470	.0221	.0323	.0205	.0300
As	.0065	.040	.013	.017	.010	.0400	.0300	.0268	Nd	.0205	.0274	.0550	.2400	.0795	.0420
Spectrographic analyses															
Si	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Al	1.5	.7	.7	7.0	1.5	3	1.5	1.5	1.5	3.0	3.0	7.0	3.0	1.5	1.5
Fe	.7	1.5	1.5	1.5	1.5	1.5	1.5	1.5	3.0	3.0	3.0	1.5	1.5	3.0	1.5
Mg	.15	.03	.03	.3	.15	.15	.3	.15	.15	.15	.15	.3	.3	.07	.03
Ca	*2.9	*1.03	*1.06	*.77	.15	.3	.3	.15	.15	.15	.15	.3	.3	.3	.07
Na	.07	.03	.03	.15	.15	.15	.15	.15	.07	.07	.07	.15	.15	.03	.03
K	.7	.3	.3	1.5	.7	.7	1.5	1.5	.7	.7	.7	1.5	1.5	.3	.3
Ti	.15	.03	.03	.3	.15	.15	.15	.15	.15	.15	.07	.15	.15	.07	.07
Mn	.07	.015	.015	.03	.03	.03	.007	.007	.03	.015	.03	.015	.015	.03	.015
Zr	.007	.007	.003	.03	.015	.015	.015	.015	.007	.015	.015	.015	.015	.007	.015
Ba	.015	.015	.015	.07	.07	.15	.03	.03	.03	.07	.03	.07	.07	.015	.07
Sr	.015	.007	.007	.03	.007	.015	.007	.007	.007	.015	.015	.03	.03	.007	.007
Ag	0	0	0	Trace	Trace	Trace	0	0	0	Trace	Trace	Trace	Trace	Trace	Trace
Co	0	*.0027	.0015	.015	.0015	.007	.007	.003	.003	.0007	.0015	.003	.003	.0007	.003
Cr	.0015	.003	.003	.03	.015	.15	.03	.015	.03	.015	.015	.015	.015	.07	.07
Cu	.003	*.004	.007	.03	.03	.03	.007	.007	.015	.007	.007	.007	.03	.03	.03
Mo	Trace	.0007	.0007	Trace	.0015	.0015	.0015	.0015	.0007	Trace	.0015	.0015	Trace	.003	0
Ni	.0015	*.0015	.0015	.007	.003	.015	.007	.003	.007	.003	.003	.003	.007	.003	.003
Pb	.0015	*.0045	.0015	.015	.015	.015	.007	.007	.007	.007	.007	.007	.015	.007	.007
Y	Trace	.0007	.0007	.003	.0007	.003	.003	.0015	.015	.0015	.0015	.003	.0015	0	.0015
Zn	*.0044	*.0075	*.0072	*.0495	*.0300	*.0900	.03	.03	.015	*.0063	*.0120	*.0384	*.1170	*.0047	*.0500

*Chemical analyses.

SAMPLES ANALYZED

1. Black Beauty mine—PMS-162-53, PMS-163-53, representative of 174.7 tons.
2. Camp Bird 12—PMS-124—126-53, PMS-135—142-53, GS-89-53, GS-90-53, representative of more than 4,859.4 tons.
3. Camp Bird 12A—PMS-127—134-53, representative of 1,097.1 tons.
4. North Mesa 5—PMS-304-53, PMS-305-53, representative of 927.0 tons.
5. North Mesa 7—PMS-307-53, representative of 196.7 tons.
6. North Mesa 10—PMS-308-53, representative of 76.3 tons.
7. Calyx 3—AEC-3-1, -2, representative of 111 tons.
8. Calyx 10—AEC-10-1, -2, representative of 102 tons.
9. Calyx 4—19 chip samples, collected by I. J. Witkind, U.S. Geol. Survey.
10. Vanadium King 1, portal 1 and 2—PMS-388—390-53, representative of 2,141.4 tons.
11. Vanadium King 3—PMS-391-53, PMS-392-53, representative of 716.1 tons.
12. Vanadium King 5—PMS-394—396-53, VK5-1, -2, representative of 194.7 tons.
13. Vanadium King 6—PMS-397-53, PMS-398-53, representative of 99.3 tons.
14. Vanadium King 7—PMS-399—401-53, representative of 421.7 tons.
15. Camp Bird 7—PMS-122-53, representative of 193.2 tons.

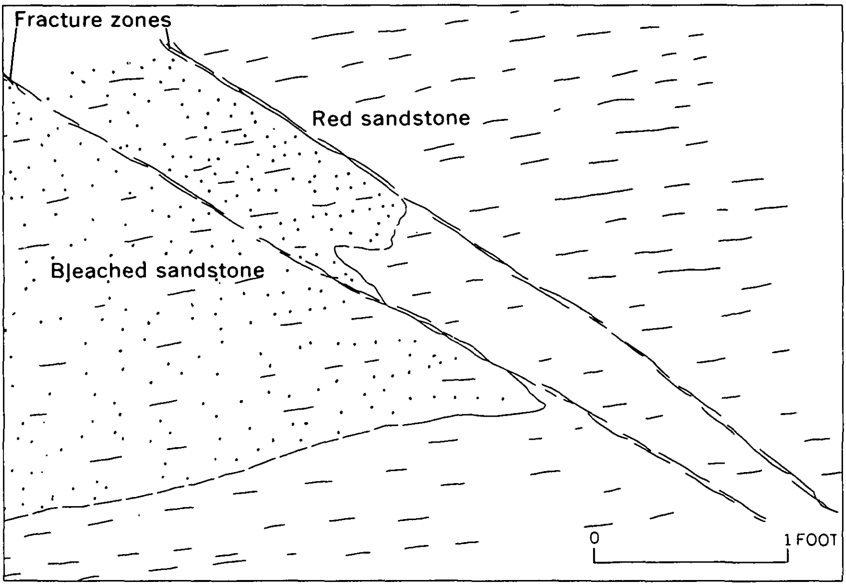

FIGURE 16.—Fracture-controlled alteration in the Church Rock Member of the Chinle Formation, Temple Mountain. Dashed lines indicate bedding.

the average[2] composition of ore from individual mines, and table 4 gives an overall average composition (weighted by production) of the ore and the average composition of some barren sandstones in the Moss Back Member. Silicon makes up more than 10 percent of the ore, and aluminum and iron generally each make up over 1 percent. Elements in the next highest range in concentration, 0.1–1.0 percent, are potassium, calcium, magnesium, titanium, uranium, and vanadium. Other elements are present in still smaller concentrations.

Organic carbon was not determined routinely in the analyses on which tables 3 and 4 are based. It was, however, determined on three of the mill-pulp samples from the Camp Bird 12 and 13 mines and on three chip samples from the Calyx 8 mine (table 5). These analyses suggest that organic carbon makes up an average of a few percent of the ore and is present in the same order of concentration in ore as are aluminum and iron. Calculations based on the grade of ore and asphaltite also indicate a carbon content of several percent. For example, if the uranium contents of ore and asphaltite are assumed to be, respectively, 0.2 and 3.0 percent, and the average carbon content

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[2] The geometric mean was reported for all analyses except one, for which an arithmetic mean was furnished the project. The geometric mean was used because the distribution of elements in both unmineralized (barren) rocks and ore has been found to be lognormal, and for a lognormal distribution the geometric mean is the best estimate of the true median (Shoemaker and others, 1959, p. 28–29). The geometric mean also has the advantage of being more stable than the arithmetic mean in respect to small variations in the numbers of samples (A. T. Miesch, oral commun., 1960).

TABLE 4.—*Average chemical composition, in percent, of ore and of barren sandstones in the Moss Back Member of the Chinle Formation*

[M, major constituent (> 10 percent); Nd, not determined. Data for Ag, in No. *1* and all data for No. *2* supplied by A. T. Miesch (written commun., 1961, 1963)]

	1	*2*	*3*		*1*	*2*	*3*
			Chemical analyses				
U	0.19	0.00028	0.001	Se	0.024	≈0.00002	0.0002
V	.38	.0040	.003	As	.026	≈.001	Nd
			Semiquantitative spectrographic analyses				
Si	M	M	M	Ba	0.036	0.046	0.03
Al	1.8	3.1	1.5	Sr	.009	.014	.003
Fe	1.9	.63	.7	Ag	.00001	.000003	0
Mg	.16	.39	.15	Co	.003	.0002	.0007
Ca	.27	4.1	1.5	Cr	.017	.0017	.0015
Na	.09	.20	.15	Cu	.008	.0009	.003
K	.89	1.8	1.5	Mo	.0008	<.0002	0
Ti	.12	.068	.07	Ni	.004	≈.0003	.0015
Mn	.013	.040	.015	Pb	.007	≈.0001	.0007
Zr	.012	.011	.015	Y	.002	.0011	.0007
				Zn	.017	≈.002	0

1. Ore, Temple Mountain. Geometric mean weighted by 1948–56 production. Computed from Nos. 1–15, table 3.
2. Barren sandstones, Colorado Plateau. Geometric mean, 30 samples.
3. Barren sandstones, Temple Mountain district. Geometric mean, 3 chip samples.

TABLE 5.—*Organic-carbon contents, in percent, of some mill-pulp and chip samples of ore from the Moss Back Member of the Chinle Formation at Temple Mountain*

[Carbon in mill-pulp samples determined directly by Alice Caemmerer; analyses furnished by A. T. Miesch. Carbon in chip samples determined indirectly (gasometric method) by I. C. Frost. Nd, not determined]

Field No.	*Lab. No.*	*Organic carbon*	*Equivalent uranium*	*Uranium*
	Mill-pulp samples			
Camp Bird 12 mine:				
PMS–141–53	--------	1.47	0.18	0.20
142–53	--------	2.41	.11	.11
Camp Bird 13 mine:				
PMS–145–53	--------	3.12	.07	.08
	Chip samples			
Calyx 8 mine:				
AEC–8–17C	253144	5.0	0.21	Nd
8–4A	253138	3.9	.075	Nd
8–5A	253139	11.6	1.2	Nd

of asphaltite, 60 percent (p. 87), then the average carbon content of ore is 4 percent (the 3 percent uranium assumed in asphaltite is less than all but one value reported in table 11 but is greater than the uranium content of the nodules studied by Breger and Deul, 1959, table 6).

Shoemaker and others (1959, p. 33–36) grouped the elements found in the Colorado Plateau uranium deposits as intrinsic and extrinsic. The intrinsic elements are those contained in detrital and diagenetic minerals unrelated to uranium mineralization. They occur in both ore deposits and unmineralized rocks in about the same concentrations. The extrinsic elements were introduced by processes related to the uranium mineralization and are "empirically defined as those elements that are more abundant in the uranium ores than in the equivalent unmineralized rocks" (Shoemaker and others, 1959, p. 35). Shoemaker and his coworkers also pointed out (1959, p. 36) that no element belongs exclusively to either the extrinsic or intrinsic group. A small amount of uranium was, for example, present as an intrinsic component of the rock at the time most of the uranium was introduced and the ore deposit formed. It also follows from the empirical definition that an element may not fall into the same classification in all deposits; if an element occurs in the same concentration in a group of deposits as in nearby unmineralized rock, it would here be classed as intrinsic, even though it might be extrinsic in most other deposits.

Organic carbon, although very abundant in ore, probably is intrinsic, because it also is present in about the same concentration in barren petroliferous sandstone as it is in ore. Sample 3 (table 10) contained about 1.9 percent oil and 1.8 percent organic carbon. The average oil content of five sandstone samples of Moss Back (table 10, Nos. 1–5) is about 3.7 percent, and the organic-carbon content of the average petroliferous sandstone is about 3.4 percent if the oil/carbon ratio is similar to that of sample 3. The intrinsic classification depends upon the probability that the sandstones were petroliferous before uranium mineralization. Some of the relations that suggest early introduction of oil have been discussed previously; others are discussed in the section "Rock Alteration."

The ratios of calcium and magnesium in ores and barren rocks point out a problem in the classification of elements as intrinsic and extrinsic. Magnesium is somewhat less abundant in ore than in barren rocks, and calcium is much less abundant in ore, but both calcium and magnesium were added as dolomite to the altered rocks adjacent to the ores; so a net gain in magnesium and a smaller loss (or gain) of calcium might well result if closely adjacent altered rocks were included with the ore in establishing the concentration ratios. Virtually the same problem pertains to certain extrinsic elements. For example, the chromium content of altered unmined rock adjacent to ore locally exceeds the chromium content of ore; the concentration ratio of chromium, computed from the concentration in ore and barren rocks, may therefore be a minimum.

The relative amount of enrichment of elements in ore is shown by concentration ratio—the concentration of an element in ore relative to its concentration in barren rock (table 6). The elements whose concentration ratios are more than 2 are considered dominantly extrinsic; those whose ratios are less than 2 are dominantly intrinsic. The elements are listed in order of decreasing amount of enrichment as judged by comparing the ores at Temple Mountain with barren sandstones of the Moss Back Member of the Chinle Formation throughout the Colorado Plateau. The extrinsic elements enriched at least 10 times are, in order of decreasing enrichment, selenium, uranium, vanadium, lead, arsenic, cobalt, nickel, and chromium. Zinc, copper, molybdenum, silver, and iron also belong to the dominantly extrinsic group, as each is enriched at least three times. Dominantly intrinsic elements in the deposits are strontium, barium, manganese, potassium, aluminum, and calcium. Silicon, although it cannot be compared accurately from semiquantitative analyses, is contained mostly in detrital grains and is also intrinsic.

TABLE 6.—*Concentration ratios of elements found in uranium deposits in the Moss Back Member of the Chinle Formation*

	$\frac{\text{Concentration in ore}}{\text{Concentration in barren sandstone}}$			$\frac{\text{Concentration in ore}}{\text{Concentration in barren sandstone}}$	
	Colorado Plateau [1]	Temple Mountain area [2]		Colorado Plateau [1]	Temple Mountain area [2]
Se	1,200	120	Ag	≈3	------
U	680	190	Fe	3	3
V	95	130	Y	2	3
Pb	≈70	10	Ti	2	2
As	26	------	Ba	.8	≈1
Co	15	4	Al	.6	≈1
Ni	≈13	3	Sr	.6	3
Cr	10	11	K	.5	.6
Zn	≈9	------	Mn	.3	≈1
Cu	9	3	Mg	.4	≈1
Mo	>4	------	Ca	.07	.2

[1] Computed from Nos. 1 and 2, table 4.
[2] Computed from Nos. 1 and 3, table 4.

In table 6, the ore is also compared with barren sandstones of the Moss Back of the Temple Mountain area.[3] With a few exceptions, the same elements are shown as intrinsic or extrinsic in both columns. The relative amounts of enrichment vary, and the ore generally shows less relative enrichment when compared with Moss Back Member sandstones than when compared with Chinle sandstones from all over the plateau. Various interpretations of the differences in enrichment are possible. One is that the sandstones near Temple Mountain had a high primary or intrinsic metal content; another is that during mineralization, small amounts of metals were added to the sandstones throughout the Temple Mountain district. The second interpretation is favored because of the obvious widespread effects of alteration in the district.

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[3] The samples are chip samples collected away from Temple Mountain. Sample TM–103 represents a 7-ft. massive sandstone bed exposed 1,100 ft. east-northeast of Temple Mountain. Sample TM–383 represents a bed about 15 ft. thick and was collected from several fresh talus blocks below the outcrop 7,500 ft. east of Temple Mountain; sample TM–387 represents a 2-ft. bed, which crops out about 1,200 ft. south-southwest of Temple Mountain.

Comparisons of concentration ratios of elements in uranium deposits at Temple Mountain with those of deposits in other parts of the San Rafael Swell and Colorado Plateau show a general similarity in the suite of extrinsic elements but wide differences in the relative amount of enrichment of certain elements (table 7). Uranium is highly enriched in all the deposits. At Temple Mountain, however, the deposits are about intermediate in relative enrichment of vanadium. Chromium and selenium are highly enriched at Temple Mountain but are only slightly enriched elsewhere. Copper, yttrium, lead, and zinc are more highly enriched in uranium deposits elsewhere in the San Rafael Swell than they are at Temple Mountain.

Certain elements classed as intrinsic in deposits at Temple Mountain also show differences in relative concentration in all deposits. At Temple Mountain strontium, magnesium, barium, manganese, aluminum, and calcium are present in about the same or smaller concentrations in ore than they are in barren rocks. At other locales in the San Rafael Swell they appear to be present in higher concentrations in ore. Although the differences between deposits at Temple Mountain and those of the two larger areas that enclose it are small, they could be significant. For example, the relative sparsity of calcium in Temple Mountain uranium deposits probably is due to removal of calcite cements by local alteration.

Ores in the Moss Back Member at Flat Top are chemically similar to ores in the Moss Back at Temple Mountain. The ore deposits at Flat Top contain smaller amounts of selenium (avg 33 ppm) and are relatively rich in vanadium and arsenic; the $V_2O_5 : U_3O_8$ ratio is almost 5 : 1, which almost equals the ratio in deposits in the Moss Back Member on North Temple Mountain.

TABLE 7.—*Concentration ratios of elements found in uranium deposits at Temple Mountain and in deposits in the rest of the San Rafael Swell and Colorado Plateau*

	$\frac{\text{Concentration in ore}}{\text{Concentration in barren sandstone}}$				$\frac{\text{Concentration in ore}}{\text{Concentration in barren sandstone}}$		
	Temple Mountain[1]	San Rafael Swell[2]	Colorado Plateau[3]		Temple Mountain[1]	San Rafael Swell[2]	Colorado Plateau[3]
U	680	460	>1,000	Y	2	5	≈8
V	95	14	490	Ag	3	-----	-----
Se	1,200	5	>6	Fe	3	2	≈4
Pb	≈70	300	>9	Ti	2	-----	2
As	26	25	>17	Ba	.8	2	≈2
Co	15	30	≈20	Al	.6	-----	2
Ni	≈13	17	≈20	Sr	≈.6	-----	≈2
Cr	10	2	≈3	K	.5	.8	≈1
Zn	≈9	18	≈2	Mn	.3	2	1.5
Mo	>4	20	>3	Mg	≈.4	1	3
Cu	9	110	7	Ca	.07	2	.7

[1] Deposits in Chinle Formation. Computed from Nos. 1 and 2, table 4.

[2] Deposits in Chinle Formation. Computed from No. 2, table 4, and from unpub. analyses.

[3] Deposits in Salt Wash Member of Morrison Formation. From E. M. Shoemaker and others (1959. table 2; written commun., 1956).

As noted by Keys and White (1956, p. 295), ore deposits in the Wingate Sandstone are relatively vanadiferous; $V_2O_5:U_3O_8$ ratios as high as 14:1 were reported. Ratios computed from mill-pulp and grab samples from the Vagabond mine (samples 1 and 2, table 8) are, respectively, about 11:1 and 21:1. Spectrographic and chemical analyses of these two samples suggest that deposits in the Wingate Sandstone contain about the same group of extrinsic elements, with the exceptions of zinc and cobalt, as do the deposits in the Moss Back, but that copper and silver are more highly enriched in the deposits in the Wingate.

Four samples of ore and altered rocks from the Vagabond mine were also analyzed for organic carbon with the following results:

Field No.	*Description* [1]	*Equivalent uranium (percent)*	*Organic carbon* [2] *(percent)*
TM-28-1A	Altered sandstone	0.005	(3)
2A	do	.004	0.6
3A	Chromium-bearing sandstone	.012	.3
4A	Asphaltite ore	.11	10.9

[1] Source of samples shown in fig. 39.

[2] Carbon determined gasometrically by I. C. Frost.

[3] Not determined because visual examination showed carbon to be very low.

TABLE 8.—*Analyses of ore and of barren rock from the Wingate Sandstone, Temple Mountain district*

[M, major constitutent (>10 percent); Nd, not determined. Analysts: C. G. Angelo, eU; H. H. Lipp, U; J. S. Wahlberg, V; G. T. Burrow, Se; R. G. Havens, semiquantitative spectrographic]

	1	*2*	*3*	*4*
Radiometric analyses				
eU	0.043	0.11	0.002	0.002
Chemical analyses				
U	0.06	0.13	Nd	Nd
V	.48	1.98	[1].007	[1].003
Se	.0025	.075	Nd	Nd
As	.025	[1]0	[1]0	[1]0
Semiquantitative spectrographic analyses				
Si	M	M	M	M
Al	7.0	3.0	1.5	3.0
Fe	1.5	.3	.7	.3
Semiquantitative spectrographic analyses—Con.				
Mg	0.7	0.15	1.5	1.5
Ca	1.5	.03	7.0	3.0
Na	.15	.15	.15	.15
K	3.0	3.0	3.0	3.0
Ag	.003	.007	0	0
Ba	.07	.015	.03	.07
Co	0	.0003	.0003	0
Cr	.015	.003	.003	.0015
Cu	.15	.3	.0015	.0007
Mo	Trace	.0007	0	0
Ni	.003	.0007	.0007	.0003
Pb	.15	.007	0	0
Y	.0015	<.003	.0015	.0007
Zn	0	0	0	0

[1] Semiquantitative spectrographic analyses.

1. Mill-pulp sample (field No. PMS-387-33) from Vagabond mine, representative of 37.3 tons (A. T. Miesch, written commun., 1956).

2. Grab sample of unoxidized asphaltite ore (field No. TM-28-4A; lab. No. 245338) from Vagabond mine.

3. Grab sample of barren basal carbonate-rich part (field No. TM-53-2B; lab. No. 245340), 7,000 ft east of North Temple Mountain.

4. Grab sample of barren part (field No. TM-53-3B; lab. No. 245341) 8 ft above sample TM-53-2B.

MINERALOGY

Most of the uranium deposits in the Temple Mountain district are unoxidized and are primary ores in the sense of being nearly unaltered from their original state. They are composed principally of a carbonaceous mineraloid termed "asphaltite." Pyrite, montroseite, uraninite, sphalerite, ferroselite, native arsenic, and, rarely, other metallic minerals accompany the asphaltite but are not nearly as abundant and are not usually visible megascopically. A few deposits in the district are appreciably oxidized and contain considerable amounts of carnotite or tyuyamunite. These deposits are probably secondary and formed by oxidation, almost in place of primary ore. Other secondary ore minerals, which generally are not abundant enough to form an ore, have formed in primary ores on fracture surfaces and on mine walls since the deposits were opened. The gangue of both primary and secondary ores is largely composed of the detrital minerals of the host rocks but locally includes carbonates and silicates formed during alteration.

In addition to the asphaltite, other carbonaceous materials, notably petroleum and coal, are found in or near the ore and in unmineralized rocks. Although the carbonaceous materials are not true minerals, they occur in the same manner as the ore and gangue minerals, and, therefore, are described in this section. The minerals and mineraloids are discussed under the following headings: "Primary Minerals," "Carbonaceous Materials," and "Secondary Minerals."

PRIMARY MINERALS

NATIVE ARSENIC

Native arsenic is found in ore deposits at several places at Temple Mountain, but it has not, to our knowledge, been found in other uranium deposits of the Colorado Plateau. In the Temple Mountain collapse structure it occurs as nodules as much as 3 inches across and is associated with pyrite, sphalerite, and asphaltite. The nodules were discovered by Jess Abernathy at the Fumerol mine; they were subsequently described by Kerr and Lapham (1954). Native arsenic also occurs in the deposits in the Moss Back Member on North Temple Mountain. At the Vanadium King 5 mine it is disseminated in blebs and lacy aggregates closely associated with sphalerite and montroseite. In the Camp Bird 7 mine it replaces flattened pebbles near ore (G. L. Chase, oral commun., 1956), and the arsenic-bearing rock is heavily stained with realgar and orpiment. Some of the very small, soft, white metallic grains seen in polished sections of Calyx Bench ores may be native arsenic.

PYRITE AND MARCASITE

Pyrite is the most common metallic mineral of the district; it occurs in the Coconino Sandstone, Moenkopi Formation, and in the Temple Mountain, Monitor Butte, and Moss Back Members of the Chinle Formation. In the greenish regionally altered rocks of the Moenkopi Formation, it commonly occurs as cubes as much as one-eighth inch across and as nodules as much as 2 inches across. Analyses of one pyrite-rich nodule (lab. No. 253127) from the Moenkopi show 1 ppm selenium and larger concentrations of chromium, copper, nickel, and arsenic as follows:

	Concentration (percent)		*Concentration (percent)*
Radiometric analysis:		Spectrographic analyses—Con.	
eU	<0.001	Co	0
Spectrographic analyses:		Cr	.0015
Si	3	Cu	.007
Al	1.5	Ni	.007
Fe	>10	Chemical analyses:	
Ag	.000015	As	.050
		Se	.0001

In the Temple Mountain and Monitor Butte Members, pyrite is found as cubes less than one-sixteenth inch across and as massive aggregates of very small crystals. The second mode of occurrence was noted only in core from drill hole V–5, near the Temple Mountain collapse. Pyrite, as nodules and disseminated crystals, is also found in the altered rocks of the collapse structures. Drill hole V–1, in the West collapse at Temple Mountain, intersects high-angle fractures in the Coconino Sandstone filled by pyrite veins.

Pyrite is widespread in the sandstones of the Moss Back but is only abundant locally, in coaly materials. It occurs as disseminated crystals and nodular masses in mineralized and barren sandstones and in several ways in uraniferous and nonuraniferous coals. The most typical modes of occurrence in coals are as (1) fillings of cells and replacements of cell walls, (2) massive intergrowths of anhedral to euhedral crystals, and (3) veinlets cutting across coaly or wood structures. In ores in which coaly materials are sparse or absent, disseminated pyrite is associated with asphaltite, sphalerite, montroseite, and ferroselite. One type of disseminated pyrite commonly associated with ore minerals is fine grained, generally microscopic, and typically zoned (fig. 17, upper photo). It is most abundant in lower grade ores. Pyrite is also found locally as microscopic grains in nodular masses of asphaltite (fig. 17, lower photo). In the nodules the pyrite occurs as tightly packed aggregates of very small crystals or as loose aggregates in which the grains appear to have been displaced radially from a common center.

Analyses for six pyrite-rich mineral separates from the Moss Back Member are shown in table 9. Heavy liquids were used to separate the pyrite from sandstone or coaly matrices; quartz, which adhered to the pyrite grains, and sphalerite were the main contaminants. Four types of pyrite occurrence are represented: pyrite in wood cell structures (samples 1 and 2), massive intergrowths of pyrite in coal (samples 3 and 4), interstitial pyrite in sandstone surrounding coal (sample 5), and nodular pyrite in sandstone away from coal (sample 6).

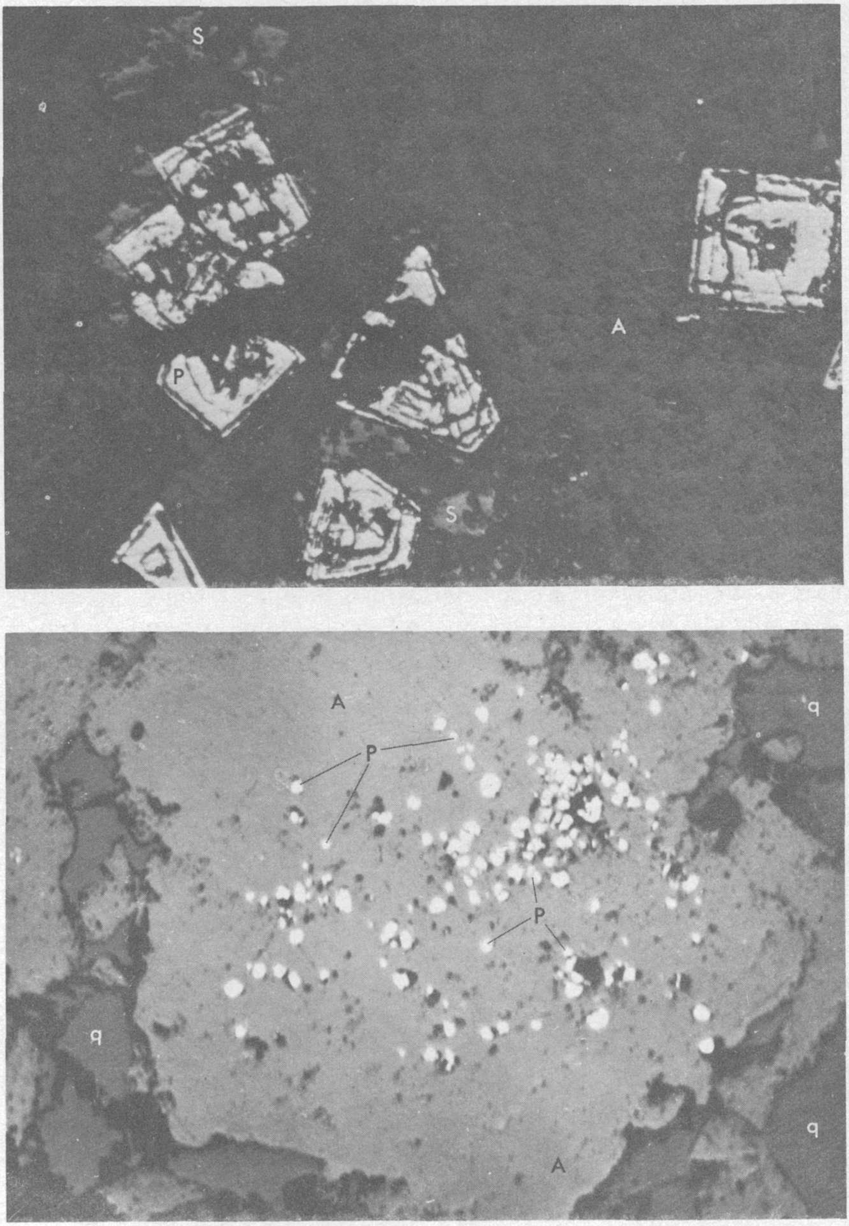

FIGURE 17.—Photomicrographs of ore. Upper photograph, zoned pyrite (P) associated with asphaltite (A) and sphalerite (S). × 190. Lower photograph, disseminated pyrite (P) in uraniferous asphaltite (A) nodule. Quartz, q. × 185.

Arsenic, manganese, and lead vary by factors of less than 5. In contrast, selenium, vanadium, zinc, and some other metals vary by factors of 10 or more. This variation is partly caused by contamination by other minerals. The relatively low selenium content of some of the samples is, however, probably significant. The selenium contents of samples 1, 2, and 6 are 25, 25, and 38 ppm, respectively, only slightly greater than the average selenium content (15 ppm) of 55 pyrite and marcasite samples collected in Chinle rocks outside the Temple Mountain district (Coleman and Delevaux, 1957, p. 516–517). The selenium contents of the aforementioned three samples closely match the average content (40 ppm) of four barren [4] pyrites collected by Coleman at Temple Mountain. The selenium contents of samples 3, 4, and 5 are much greater; this probably is partly caused, at least in samples 3 and 4, by the presence of ferroselite, the iron selenide. The relatively high zinc content of samples 1–5 is due probably to the presence of sphalerite, which is typically found in vitrain.

Not all the pyrite of the Temple Mountain district formed in the same way, and much of it is probably unrelated to ore. The altered part of the Moenkopi Formation, which is pyritiferous, apparently is unrelated to the altered rocks near Temple Mountain, and the pyrite in the Moenkopi is inferred to have formed during a period of regional alteration that preceded(?) the Temple Mountain alteration. At least some of the pyrite in the Temple Mountain and Monitor Butte Members may be related to the alteration at Temple Mountain. Near the Temple Mountain collapse structure pyrite aggregates in the aforementioned members resemble in distribution and in form hematite concentrations found in those same members farther from Temple Mountain. The hematite concentrations formed during the regional alteration of the members, and the pyrite concentrations found near the collapse may have formed pseudomorphically after this type of hematite.

Pyrite in the Moss Back Member also probably reflects more than one mode of origin. The different modes of occurrence of pyrite in the coals apparently represent, at least in part, different generations of deposition. The pyrite in the cells and cell walls is oldest; it was deposited before plastic deformation of organic parts of the coal and before the deposition of an early generation of sphalerite. The pyrite in veinlets, and probably that in massive intergrowths, is younger than the early sphalerite but is older than most of the asphaltite and associated metallic minerals. The pyrite found in the cell structures of the coal is low in selenium (samples 1 and 2, table 9), and in view

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[4] Barren sulfides were collected by Coleman away from ore bodies in rock containing less than 0.01 percent U_3O_8.

TABLE 9.—*Analyses, in percent, of pyrite-rich mineral separates*

[M, major constituent (>10 percent). Analysts: C. G. Angelo, eU; G. T. Burrow, Se; Claude Huffman, Jr., As; H. H. Lipp, V_2O_5; C. S. Annell, spectrographic]

Sample	Field No.	Lab. No.	Radiometric and chemical analyses				Semiquantitative spectrographic analyses												Remarks
			eU	Se	As	V_2O_5	Si	Al	Fe	Ti	Mn	Ag	Co	Cr	Cu	Ni	Pb	Zn	
1	NM-1-2	253471	0.003	0.0025	0.24	0.51	0.15	0.03	M	0.0015	0.03	0.00015	0.03	0	0.07	0.015	0.03	0.3	Pyrite in cells and cell walls in vitrain; no uranium minerals noted. Minor amounts of sphalerite seen in polished section.
2	AEC-8-20	253470	.001	.0025	.35	<.05	.3	.03	M	0	.03	.0003	.07	0	.15	.03	.07	.7	Do.
3	AEC-8-29A	253464	.003	.0700	.34	1.83	.3	.15	M	.03	.07	.00003	.015	.00015	.07	.015	.015	1.5	Massive growth of subhedral pyrite in coaly material; highly stained by corvusite, surrounded by asphaltite ore. Some ferroselite present in adjacent ore.
4	AEC-8-26	253465	.19	.0200	.10	6.52	7	1.5	M	.03	.03	.00003	.007	.0015	.007	.015	.015	.07	Do.
5	SR-10A-56	253467	.009	.0260	.39	.34	3	.3	M	.03	.03	.0003	.015	.03	.015	.015	.015	.7	Pyrite interstitial to sand grains, surrounding vitrain, and in turn surrounded by asphaltite.
6	AEC-8-18	253465	.044	.0038	.089	.15	M	.3	M	.03	.03	.00003	.0015	.0007	.003	.0015	.015	.07	Pyrite, nodular impregnation of sandstone, apparently not associated with carbonaceous material.

of the extensive addition of selenium at Temple Mountain and the apparent early paragenetic position of this pyrite we regard the cell-structure pyrite as being diagenetic and unrelated to the uranium mineralization. The fine-grained zoned pyrites disseminated in the ores are closely associated with asphaltite and ore minerals and are regarded as "ore pyrites." Pyrites other than the cell-structure and zoned types cannot be reasonably assigned, on the basis of present information, to either diagenetic or ore-forming periods.

The mode of occurrence of marcasite in the Moss Back rocks is similar to that of pyrite, but marcasite is much less abundant. In coaly materials it is generally present in the cells or cell walls.

FERROSELITE

Ferroselite ($FeSe_2$) resembles marcasite in megascopic appearance and in structure, but in polished section it differs from marcasite in having a faint rose cast in ordinary light and in showing bronze and purple colors under crossed nicols. It was first identified at Temple Mountain by Coleman and Delevaux (1957, p. 510), who found the mineral associated with pyrite and coalified wood in the Calyx 8 mine.

Ferroselite has also been found in bands parallel to the contacts of ore deposits and as disseminations within asphaltite ore; ferroselite or a related cobalt-bearing mineral probably is also present in dolomite-cemented masses peripheral to ore bodies. Ferroselite bands were observed adjacent to a small ore zone in the Calyx 8 mine (fig. 36) and adjacent to a hand-specimen-size roll in the North Mesa 9 mine. The ferroselite in both these places occurs as subhedral to euhedral crystals in the interstices of sandstone adjacent to high-grade ore. This occurrence of ferroselite is nearly identical to occurrences of ferroselite or other selenium minerals in some vanadium and uranium deposits in the Entrada, Navajo(?), and Morrison Formations elsewhere on the Colorado Plateau (Coleman and Delevaux, 1957, p. 506). A concentrate (lab. No. 253466) obtained from the bands in the Calyx 8 mine showed the following:

	Concentration (percent)
Radiometric analysis:	
eU	0.028
Chemical anlayses:	
Se	40.6
As	.11
Spectrographic analyses:	
Si	>10
Fe	>10
Co	.07
Cu	.015
Ni	.07
Pb	.07
Zn	.7

A pyritelike mineral disseminated in dolomitic masses peripheral to ore in the Moss Back Member may be ferroselite but is more likely a related cobalt-bearing mineral because cobaltomenite (cobalt selenite) commonly coats the dolomite.

SPHALERITE AND OTHER SULFIDES

A light-colored variety of sphalerite is the third most abundant metallic mineral, ranking after pyrite and montroseite. It occurs in uraniferous and nonuraniferous coals, is disseminated in the ores, and is also associated with pyrite and chalcopyrite, in the chert-carbonate veins of the regionally altered Temple Mountain and Monitor Butte.

Sphalerite in the coals has two modes of occurrence and formed in two generations. One variety of sphalerite is in microscopic blebs (fig. 28, lower photo) in a banded structure of the vitrainlike coals. The other, later type is in fractures that cross the vitrain structure and is invariably associated with montroseite or microscopic pyrite crystals.

Sphalerite as microscopic anhedral crystals about 0.1 mm across was identified in asphaltite ores from the Calyx Bench, from North Temple Mountain, and from the Temple Mountain collapse. In higher grade ores, sphalerite is commonly peripheral to the asphaltite; in lower grade ores it is scattered through the sandstone together with small blebs of asphaltite.

Galena is common but not abundant in the ore deposits of the Moss Back Member. In these ores it generally is in microscopic crystals; megascopic crystals of galena were found in somewhat uraniferous coaly material from the North Mesa 2 and Camp Bird 7 mines.

Galena is a more important component of mineralized rock in the basal part of the Moenkopi and upper part of the Coconino in the Temple Mountain collapse; here, the galena is commonly visible in hand specimens. Galena is particularly abundant in the rocks cut by drill hole V–1, where it occurs in two zones: the first (upper) in partly brecciated sandstone, mudstone, and chert between 364 and 374 feet below the collar and the second in slightly fractured sandstone between 403 and 441 feet. In the upper zone, where the rocks are derived from the Moenkopi and Kaibab(?) Formations, the galena is associated with uraniferous asphaltite and minor amounts of pyrite, hematite, and chromium-bearing silicates, which occur in veins and steeply plunging pipes. In the lower zone, where the host rock is slightly fractured Coconino Sandstone, the galena occurs as small disseminated crystals (less than 2 mm across). In drill hole V–5, galena is found with uraniferous asphaltite and chromium-bearing silicates in the uppermost 10 feet of the Coconino. Galena has also been reported from drill hole V–7, in the East collapse, and from drill hole V–9, in the small collapse 3,000 feet west of the Flopover (Keys and White, 1956, p. 291–293).

Small amounts of chalcopyrite are found in the asphaltite ores of the Moss Back Member, in chert-carbonate veins in the regionally altered Temple Mountain and Monitor Butte Members of the Chinle, and in the Sinbad Limestone Member of the Moenkopi Formation about 2,000 feet west of North Mesa 9 mine.

According to D. M. Hausen (1959, p. 14, 15) three other copper-bearing sulfides—bornite, chalcocite, and covellite—are found in deposits in the Wingate Sandstone at Temple Mountain.

URANINITE AND UNIDENTIFIED RADIOACTIVE MATERIALS

Uraninite and possibly other uranium-bearing substances are found in and adjacent to asphaltite in the primary ores of the district. Some of the uraninite is visible under the microscope at relatively low magnifications (less than × 100), and this relatively coarse material occurs in asphaltite in irregular, apparently fractured grains showing an "ice-cake" texture (fig. 18). A much finer grained gray mineral resembling uraninite occurs in a different fashion. Examination of polished sections at 400 diameters or more shows rounded blebs of the gray mineral concentrated on boundaries between light- and medium-gray asphaltite.

The presence of uranium in submicroscopic form is shown by asphaltite, which is homogeneous in polished section and shows a uni-

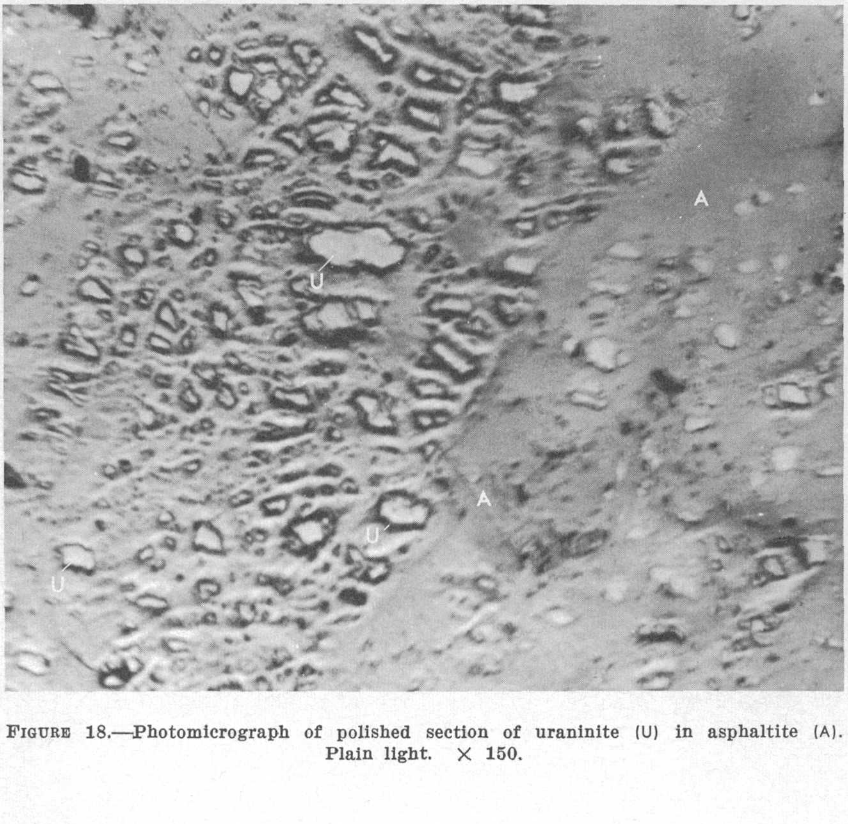

FIGURE 18.—Photomicrograph of polished section of uraninite (U) in asphaltite (A). Plain light. × 150.

form distribution of radioactivity on autoradiographs. The uranium in this type of asphaltite could be contained in very fine grained, uniformly distributed uraninite or, perhaps, in a urano-organic complex.

MONTROSEITE AND PARAMONTROSEITE

Montroseite (VO(OH)), described by Weeks, Cisney, and Sherwood (1953), or its alteration product paramontroseite (VO_2), is the most common metallic mineral in the district other than pyrite. In polished section montroseite has a metallic-gray color, typically has negative relief, and is moderately anisotropic in bronze, bluish, and faint green colors. The montroseite is commonly in aggregates of elongate crystals or, less commonly, occurs as isolated acicular crystals. Typically the crystal aggregates occur interstitially to sand grains (fig. 19, upper photo) in rocks partly replaced by asphaltite. Aggregates of montroseite also occur in veinlets cutting silicified (fig. 19, lower photo) or coalified wood. Microscopic acicular crystals of montroseite are associated with pyrite in ore from the Marchbank incline and native arsenic from the Vanadium King 5 mine.

HEMATITE AND LIMONITE

Hematite and limonite are concentrated in altered rocks near the Temple Mountain collapse structure and are the coloring agent of the fine-grained sedimentary rocks of the district. Most of the hematite and limonite found near the collapse is of secondary origin and formed by the oxidation of siderite (Keys and White, 1956, p. 289), which occurs in fresh exposures of the ferruginous rocks. Some of the hematite and limonite may, however, be primary. Hematite occurs with galena and chromium-bearing silicates in unweathered rocks at depth in the collapse. Hematite and limonite (variety, goethite) are found in outcrops 200 feet north-northeast of the Young prospect (AI-1, fig. 3), where they form massive botryoidal intergrowths as much as a foot across which do not seem to be pseudomorphous after siderite. The botryoidal masses are fractured and veined with soft nonuraniferous asphalt, which appears to be of recent probably near-surface origin.

CARBONATE MINERALS

Carbonate minerals found in the district are calcite, dolomite, and siderite. Calcite is a common mineral cement in unaltered rocks and probably formed in diagenesis; it is rare in altered or mineralized rocks. Dolomite and siderite are common in the altered rocks near Temple Mountain. Dolomite is mainly in the Wingate Sandstone and siderite is mainly in the Church Rock Member of the Chinle; they occur both in tabular zones along bedding and in irregular zones

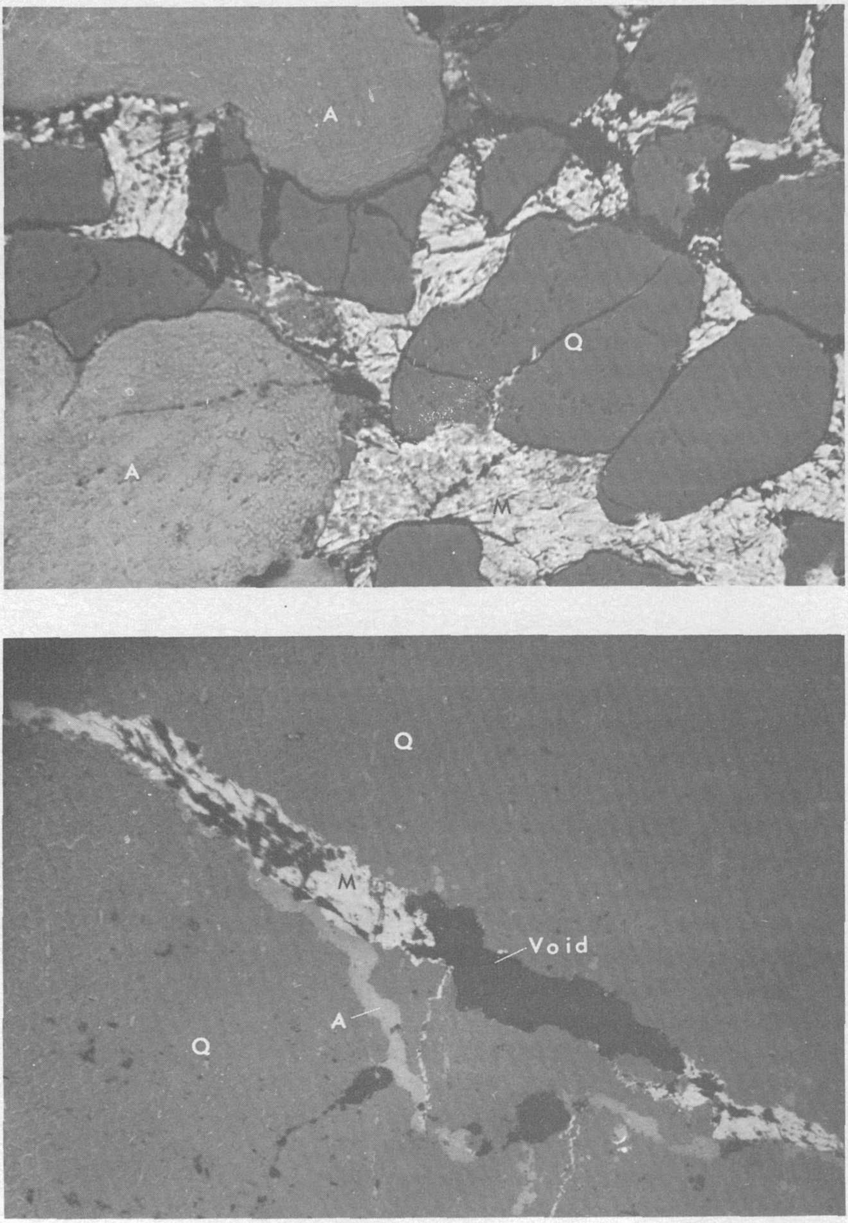

FIGURE 19.—Photomicrographs of ore, showing montroseite (M) in interstices of sandstone, × 63 (upper photo.), and silicified wood (Q) veined with montroseite (M) and asphaltite (A), × 55 (lower photo.).

across bedding. As recognized by Kerr and others (1955), the carbonates replace primary and diagenetic rock constituents; the amount of replacement ranges from limited, where interstitial cements have been replaced in dolomite-cemented nodules, to nearly complete, where nearly the entire rock has been converted to dolomite. Modal analyses and insoluble residues of partly dolomitized rocks show that the dolomite preferentially replaces feldspar, chert, and interstitial materials before it replaces the crystalline quartz of the rocks. In the most intensely dolomitized zones, as near the base of the Wingate on the west side of South Temple Mountain, relatively pure dolomite crystals line vugs in zones composed of crystalline dolomite. A semiquantitative spectrographic analysis of a dolomite sample (lab. No. 253154) showed the following:

	Concentration (percent)		*Concentration (percent)*
Si	0.15	Ca	>10
Al	.07	Ba	.0015
Fe	.15	Cu	.0015
Mn	.07	Pb	.0015
Mg	>10	Sr	.007

Dolomite also occurs in crosscutting replacement zones adjacent to ore deposits in the Moss Back Member and in the Wingate Sandstone. Partly dolomitized zones as much as 3 feet across are found on the concave side of rolls or below tabular ore zones of the Moss Back Member. The dolomite in these zones replaces the interstitial cements and in places markedly corrodes and embays the sand grains (fig. 20). As previously noted this dolomite contains pyritelike minerals that are probably selenides. Other partly dolomitized zones, ranging from 25 feet to several hundred feet across, underlie the ore bodies in the Wingate Sandstone; the dolomite in the Wingate locally contains disseminated copper sulfides.

SILICATES

Silicate minerals of detrital origin, especially quartz, form most of the host rocks for the uranium deposits. The effects of alteration on detrital quartz and feldspar are seen mostly in development of quartz overgrowths or in solution evidenced by embayment of the grains. The quartz grains in ore are embayed by asphaltite and in dolomitized zones by dolomite; the quartz grains in otherwise altered zones generally have euhedral quartz overgrowths. The clay minerals in sandstones and mudstones are also dominantly detrital in origin, but some clay minerals formed epigenetically and most clay minerals in or near ore were modified in composition and appearance during mineralization.

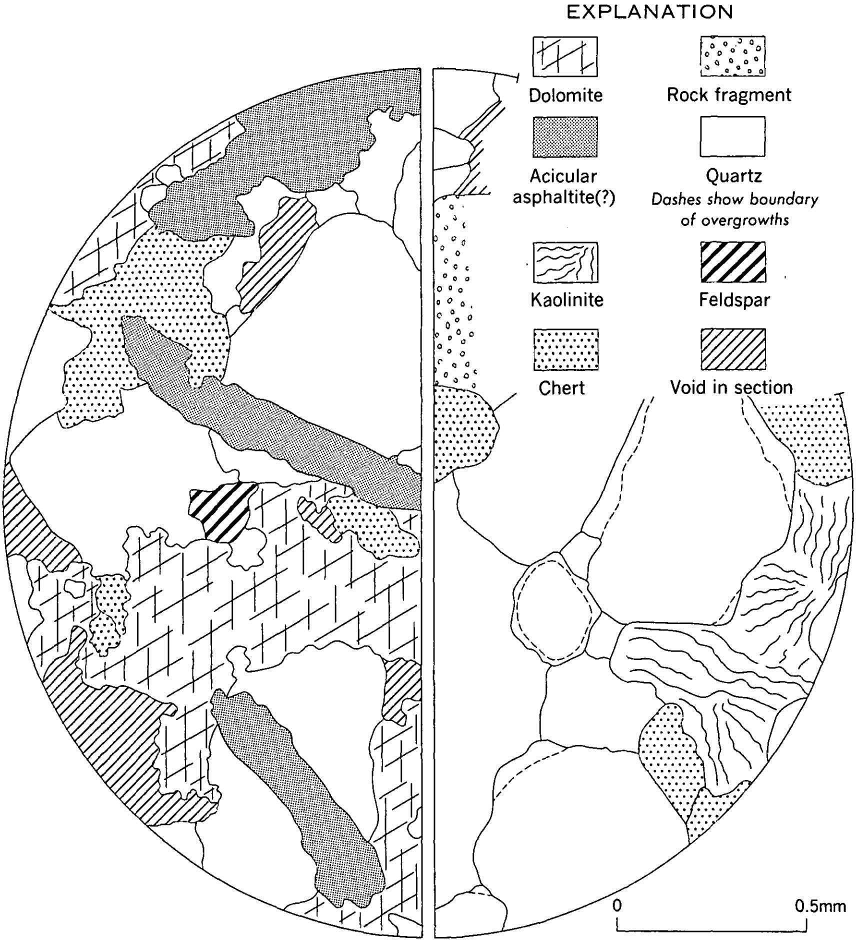

FIGURE 20.—Camera-lucida drawings of adjacent dolomitic and nondolomitic areas in altered sandstone in the Moss Back Member.

Clay minerals found in the host rocks include kaolinite, illite, and mixed-layer illite-montmorillonite. Koalinite can generally be distinguished in thin section, but the illite and mixed-layer clay cannot; and throughout most of this report both are referred to as mica clays.

Kaolinite is probably the most abundant clay mineral in most sandstones; it is dominantly interstitial and is visible megascopically as white blotches in the interstices. In thin section the kaolinite appears as very finely crystalline aggregates and as somewhat coarser vermicular forms.

X-ray diffraction studies made on mudstones from the Calyx 8 mine by L. M. Schultz of the U.S. Geological Survey suggest that illites are the dominant components of mudstone and that quartz, kaolinite, and mixed-layer clays make up less than half the constituent parts.

In and near ore the mudstones and interstitial flakes of clay in sandstone are either bright green or dull gray to almost black in contrast to their pale-green color away from ore. The bright-green mudstones and clay minerals are found in altered rocks near ore; the gray to black mudstones and clay minerals occur in ore or in direct contact with ore-bearing rocks. The green clays are most obvious in the deposits in the Wingate Sandstone but also occur near deposits in the Moss Back Member and in the Temple Mountain collapse structure.

Most of the clay minerals in mudstone are shown by mode of occurrence to be of detrital origin, although their color and composition may have changed as the result of alteration. Some green and gray clay minerals occur in veinlets or replace detrital grains in sandstones and so were formed epigenetically.

The green mudstones and disseminated clay minerals are chromiferous, and probably both green and gray mudstones and disseminated clay minerals are generally vanadiferous. Semiquantitative spectrographic analyses of a light-green micaceous clay mineral from the Calyx 8 mine indicated 0.3 percent chromium in addition to more than 10 percent of both silicon and aluminum, 7 percent potassium, 0.7 percent iron and titanium, 1.5 percent magnesium, 0.3 percent vanadium, and smaller amounts of other elements. X-ray analyses of the same sample showed a muscovitelike pattern (R. P. Marquiss, written commun., 1956). Spectrographic analyses of gray and green mudstones, largely composed of illite, generally showed a few tenths percent vanadium.

Chromium-bearing clay minerals from Temple Mountain studied by Kerr and Hamilton (1958) contained about 0.4–3.3 percent Cr_2O_3 (about 0.3–2.3 percent Cr) and were mainly composed of mixtures of $2M_1$ and 1M mica polymorphs; they were termed "mica-clays" by Kerr and Hamilton and probably are about the same as the illites of this report.

Relatively coarse mica clays in which individual crystals are recognizable in thin section occur in some ores and altered rocks. They vein coarse kaolinite and replace quartz and other detrital minerals along grain contacts; locally they rim botryoidal masses of asphaltite.

CARBONACEOUS MATERIALS

Uraniferous asphaltite is the chief introduced component of the ore deposits, and petroleum, asphalt, and coal are widely distributed in the host rocks. Petroleum, with subordinate amounts of asphalt, is a conspicuous component of several formations; coal is confined to the Chinle Formation.

PETROLEUM AND ASPHALT

The petroleum of the Temple Mountain district is a brown to almost black, heavy, asphalt-base oil; it is fluid enough to drip from fresh surfaces of saturated rocks and from fractures and drill holes. The asphalt is a lustrous black solid that breaks conchoidally but also has the property of viscosity and becomes noticeably softer with a slight increase in temperature. Both the petroleum and asphalt are partly soluble in carbon disulfide. The asphalt is translucent and optically isotropic; it is softer than the uraniferous asphaltite, which also contrasts in its insolubility in carbon disulfide, in its opacity, in its anisotropism, and in its much higher uranium content.

Petroleum occurs in varying concentrations in the coarser grained rocks of the district. It is present locally in all exposed formations up to and including the Navajo Sandstone. It is particularly abundant in the upper part of the Coconino Sandstone, the Kaibab Limestone, the Sinbad Limestone Member and sandstones of the Moenkopi Formation, and the Moss Back Member of the Chinle Formation. It is abundant in the Wingate Sandstone at Temple Mountain and is found in rocks of the collapse structures. Fine-grained silty sandstones of the Church Rock Member of the Chinle Formation and of the Moenkopi Formation, nonpetroliferous elsewhere, are locally petroliferous adjacent to the collapses.

The asphalt occurs in fracture fillings, vugs, and in interstices of altered rocks. Asphalt in vugs and fractures is found in the Kaibab Limestone, the Moenkopi Formation, the Moss Back Member of the Chinle, and, at Temple Mountain, in the Wingate Sandstone. In these occurrences, the asphalt fills fractures that cut ore bodies in the Moss Back Member, veins altered rocks in the Temple Mountain collapse, and partly fills vugs in altered Wingate Sandstone.

The interstitial asphalt occurs in altered rocks near ore or near collapse structures. Locally the altered zones are cut and displaced by fractures containing vein asphalt, and the interstitial asphalt probably is older than the asphalt in vugs and fractures. The interstitial asphalt forms part of the cement in altered friable sandstones, which are composed mainly of quartz with overgrowths (fig. 21). It ranges in abundance from sparsely disseminated blebs in bleached parts of the Wingate Sandstone and rocks in collapse structures to abundant blebs, which give altered sandstones of the Moss Back a characteristic salt-and-pepper appearance. The blebs are nearly equidimensional to slightly elongate but in detail are irregular because of indentations caused by overgrowths on quartz grains. Unlike the massive asphaltite found in ore, the interstitial asphalt shows no tendency to replace quartz. Within a few feet from ore, however, the asphalt grades into an acicular asphaltitelike substance, which locally does replace quartz. The acicular asphaltite(?) forms needles less than one-sixteenth inch across and as much as one-third inch long. The needles are partly interstitial but also cut through quartz grains (fig. 22).

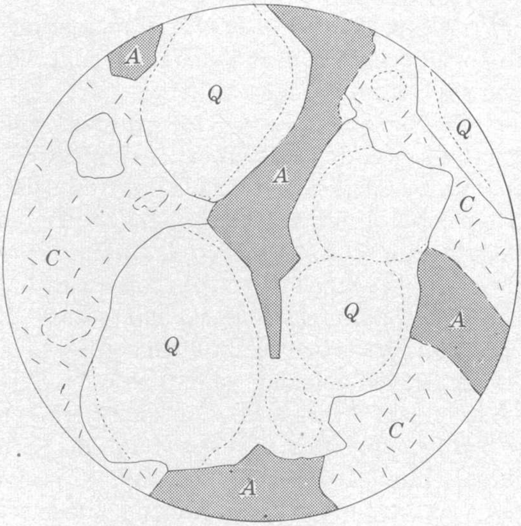

FIGURE 21.—Interstitial asphalt (*A*) in sandstone of the Moss Back. *Q*, quartz; *C*, interstitial clay. Approximately × 80.

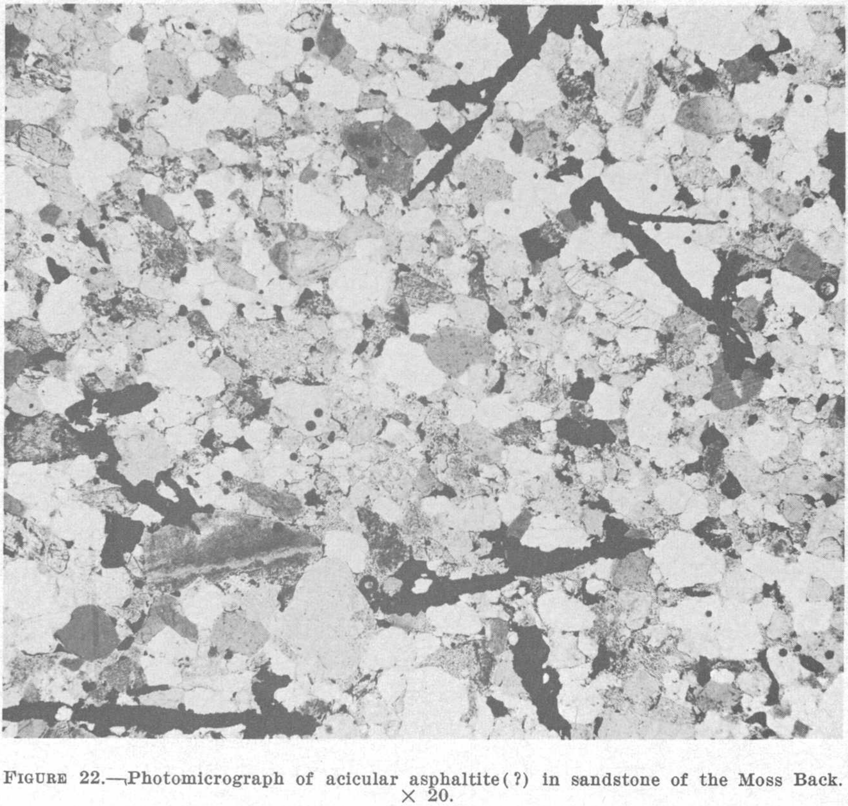

FIGURE 22.—Photomicrograph of acicular asphaltite(?) in sandstone of the Moss Back. × 20.

The interstitial asphalt is translucent in thin section; the acicular asphaltite(?) is opaque except near its contacts and where it appears to grade into the interstitial asphalt.

A detrital origin has been proposed for asphaltic material like the interstitial asphalt discussed in this report. Hess wrote (1933, p. 456) that "the asphaltite was deposited as rolled grains, some hard enough to hold their shape and others so soft that they were deformed into a cement for the siliceous sand." Although this interpretation is consistent with the indented shape of some of the asphalt blebs, it does not account for the fact that interstitial asphalt occurs only in altered rocks near ore or collapse structures and that the asphalt apparently grades into the epigenetic, acicular asphaltite (?). Also, the asphalt is indented by secondary overgrowths on quartz rather than by primary detrital grains. In view of these relations, a more probable explanation of the interstitial asphalt is that it is a residue of oil which was displaced by the solutions causing alteration effects, such as the formation of the secondary overgrowths on quartz.

Petroleum from the Moss Back Member of the Chinle Formation, the Moenkopi Formation, and the Wingate Sandstone was extracted,[5] filtered, ashed, and analyzed spectrographically and chemically for the inorganic constituents (table 10). The ash yielded by the oils analyzed ranged from 0.226 to 8.948 percent.

The trace elements generally present in the largest concentrations in the ash of the oil are copper, nickel, vanadium, and zinc; the elements silver, cobalt, chromium, lead, and zirconium are consistently present but in smaller concentrations. Tin is present in 6 of the 10 samples. Selenium was determined chemically in five of the samples; its concentration ranges from less than 1 ppm to 362 ppm; the two selenium-rich samples are both from the Moss Back Member on Temple Mountain.

Uranium is consistently present in the petroleum but in widely varying concentrations; the uranium content of the ash ranges from 20 to 50,110 ppm, or from 0.25 to 440 ppm of the oil. The great range in uranium concentration seems characteristic of oils extracted from the Moss Back Member; the samples from the Moss Back Member include the extremes of the known range; the uranium contents of four other samples of oil from the Moss Back studied by Breger and Deul (1959, p. 141) ranged from 0.44 to 310 ppm.

All the oils of the district are abnormally uraniferous compared with samples of 29 crude-oils collected by Erickson, Myers, and Horr (1954, table 1 and p. 2211, 2212) from wellheads in areas outside the Colorado Plateau. Of those samples, 19 contained less than 0.002

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[5] Petroleum was extracted in a Soxhlet extractor using a hot solution of benzene and other organic compounds.

ppm uranium and none contained more than 0.064 ppm. A complicating factor, however, is that oils extracted in the laboratory (by Soxhlet extractor) from petroliferous rocks typically contain more uranium than do oils collected at the wellhead (Erickson and others, 1954, p. 2211). Heavier oil fractions left in the rock thus might contain more uranium, and perhaps other metals, than would the oil pumped from the rock. Crude oils have also been found to selectively pick up uranium from uraniferous aqueous solutions (A. T. Myers, oral commun., 1956), so oils from uraniferous areas and provinces would be likely to contain abnormal concentrations of uranium.

The black lustrous asphalt occurring in fractures in the Moss Back Member contains a trace-element suite similar to that of the petroleum. The asphalt, however, is characterized particularly by high-nickel and vanadium contents, as shown in the following table of spectrographic analyses,[6] in percent, of ash from two samples of asphalt:

	1	*2*		*1*	*2*
Chemical analyses of asphalt					
Ash	0.428	0.581	U in asphalt	0.00016	0.00037
U in ash	.378	.064	As in asphalt	.004	.0015
Semiquantitative spectrographic analyses of asphalt ash					
Ag	.003	.003	Pb	.03	0
Co	.015	.015	Sn	0	0
Cr	.15	.15	V	>10	>10
Cu	.15	.3	Zn	0	0
Mo	.07	.15	Zr	.07	.07
Ni	>10	>10			

1. Sample (lab. No. 253453) from Calyx 8 mine.
2. Sample (lab. No. 253452) from Vanadium King 1 mine.

The interstitial asphalt found near ore in the altered sandstone is only slightly radioactive. Asphalt separated from a chromiferous sandstone in the Calyx 8 mine contained less than 0.002 percent equivalent uranium.

The organic composition of fractions of extracted Temple Mountain oils was studied by Breger and Deul (1959, p. 141). About 20 percent of the oil was found to consist of heavy complex hydrocarbons, the asphaltenes. The average carbon to hydrogen atomic [7] ratio of the asphaltene fractions of four oils was 1:1.23. The asphaltenes contained an average of about 5.7 percent sulfur and 0.9 percent nitrogen (both determined by combustion) and about 2.2 percent oxygen (by difference); although making up only a small fraction of the oil, they contained 63.4–82.6 percent of the total uranium of the oil.

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[6] Analysts: D. L. Ferguson, C. A. Horr, and C. S. Annell.

[7] $\frac{\text{Percent C}}{\text{Atomic weight C}}:\frac{\text{percent H}}{\text{atomic weight H}}$.

TABLE 10.—*Analyses, in percent, of oil extracted from rocks of the Temple Mountain district*

[Semiquantitative spectrographic and chemical analyses: Upper line of figures gives analyses of oil ash; lower line gives calculated analyses of oil $\left(\text{percent element in ash} \div \frac{100}{\text{percent ash}}\right)$. Symbols: Nf, looked for but not found; Nd, not determined; M, major constituent (>10 percent); Nr, not reported. Ge was looked for but not found in any sample. Analysts: E. J. Fennelly, U; C. A. Horr and D. L. Ferguson, oil, ash of oil, As, and Se; J. C. Hamilton, N. M. Conklin, and A. T. Myers, spectrographic]

Sample	Field No.	Lab. No.	Stratigraphic unit	Location	Oil in rock	Ash of oil	Chemical analyses		Semiquantitative spectrographic analyses					
							U	Se	Si	Al	Fe	Mg	Na	Mn
1	NM-9-2	245355	Moss Back Member (sandstone).	North Mesa 9 mine.	2.05	0.226	0.0538 .00012	--------- 0.0362	Nf ---------	0.7 0.0015	0.7 .0015	1.5 .003	Nf ---------	0.03 .00007
2	SR-10-56	245356	do	Vanadium King 1 mine, portal 2.	1.80	.875	5.011 .044	--------- .0158	Nf ---------	7 .06	M .09	1.5 .015	0.7 .006	.15 .0015
3	AEC-8-25A	253110A	do	Calyx 8 mine	1.94	.312	1.15 .0036	--------- <.0001	Nf ---------	.7 .002	.7 .002	M >.03	7 .02	.03 .00009
4[1]	RE-329	70120	do	Flat Top Mesa	4.66	2.92	.17 .0049	Nd Nd	7 .2	1.5 .04	1.5 .04	3 .09	.7 .02	.7 .02
5[1]	RE-330	70121	do	North Mesa 9 mine.	7.99	1.23	.002 .000025	Nd Nd	M >.1	M >.1	.7 .09	.15 .002	.15 .002	.003 .0004
6	TM-22	245357	Moenkopi Formation (sandstone).	North Temple Wash.	2.99	2.316	.0072 .00017	--------- .00021	Nf ---------	.7 .02	7 .2	7 .2	0 0	.3 .007
7[1]	RE-303	68212	do.[2]	1 mile W. of Temple Mountain.	Nr	4.86	.003 .00015	Nd Nd	M >5.	7 .03	1.5 .07	1.5 .07	.3 .015	.03 .0015
8	TM-360A	253111A	Wingate Sandstone (basal part).	North Temple Mountain, roadcut.	1.60	8.948	.006 .0005	--------- <.0001	Nf ---------	3 .3	3 .3	3 .3	.7 .06	.03 .003
9[1]	RE-332	70123	Wingate Sandstone.[2]	Flopover, Temple Mountain.	2.80	1.63	.41 .0067	Nd Nd	M >1.6	7 .1	3 .05	1.5 .02	.7 .01	.003 .00005

Sample	Semiquantitative spectrographic analyses—Continued													
	Ag	As	Be	Cd	Co	Cr	Cu	Mo	Ni	Pb	Sn	V	Zn	Zr
1	0.03	0	0	0.15	0.15	0.03	3	0.015	3	0.15	0.07	1.5	M	0.015
	.00007	0	0	.0003	.0003	.00007	.007	.0003	.007	.0003	.00015	.003	>.02	.00003
2	.015	0	.003	Nf	.15	1.5	1.5	.007	.7	.07	.03	1.5	3	.03
	.00015	0	.00003	-----	.0015	.015	.015	.00006	.006	.0006	.0003	.0015	.03	.0003
3	.007	[3].97	0	<.1	.07	.03	.3	.007	1.5	.015	.007	1.5	.15	.007
	.00002	.003	0	<.0003	.0002	.00009	.0009	.00002	.005	.00005	.00002	.005	.0005	.00002
4 [1]	.00015	0	0	0	.0015	.15	.03	0	.15	.003	0	.3	.015	.0015
	.000004	0	0	0	.00004	.004	.0009	0	.004	.00009	0	.009	.0004	.00004
5 [1]	.00015	0	0	0	.0015	.3	.03	.003	.15	.007	0	.3	0	.015
	.000002	0	0	0	.00002	.04	.004	.0004	.002	.0009	0	.04	0	.0002
6	.007	0	0	0	.015	.007	07	0	.15	.007	.015	.15	.15	.015
	.0002	0	0	0	.00035	.0002	.002	0	.0035	.0002	.00035	.0035	.0035	.00035
7 [1]	Trace	0	Trace	0	.0007	.03	.15	0	.03	.03	.003	.15	.015	.007
	Trace	0	Trace	0	.00003	.0015	.007	0	.0015	.0015	.00015	.009	.0007	.0003
8	.0007	[3].0045	0	0	0	.007	.07	0	.15	.007	0	.3	0	.007
	.00006	.0004	0	0	0	.0006	.006	0	.015	.0006	0	.03	0	.0006
9 [1]	.0003	0	.00015	0	.007	.15	.15	.007	.15	.015	.015	.3	.03	.03
	.000005	0	.000002	0	.0001	.002	.002	.0001	.002	.0002	.0002	.005	.0005	.0005

[1] Analyses from Erickson, Myers, and Horr (1954, table 111); reported to conform to more recent analyses.
[2] Petroliferous.
[3] Chemical determination.

Infrared analyses of the oils by L. D. Frederickson, Jr., Spectran Laboratories, Denver, show that aliphatic or chainlike organic molecules predominate but that considerable amounts of aromatic or ring-type organic molecules are also present. Aliphatic C–H groups absorb strongly at about 3.5 μ (microns), and CH_2 and CH_3 groups absorb at about 6.85 and 7.3 μ, respectively (fig. 23). Aromatic groups cause the absorptions in the range 11.5–13.5 μ; the presence of structurally combined oxygen is shown by the small carbonyl (C=O) absorption near 5.9 μ.

ASPHALTITE

THE TERM "ASPHALTITE"

A solid, black carbonaceous material is the host of most of the uranium in the unoxidized or primary deposits. This material has been called urano-organic ore, uranium hydrocarbon, and thucho-

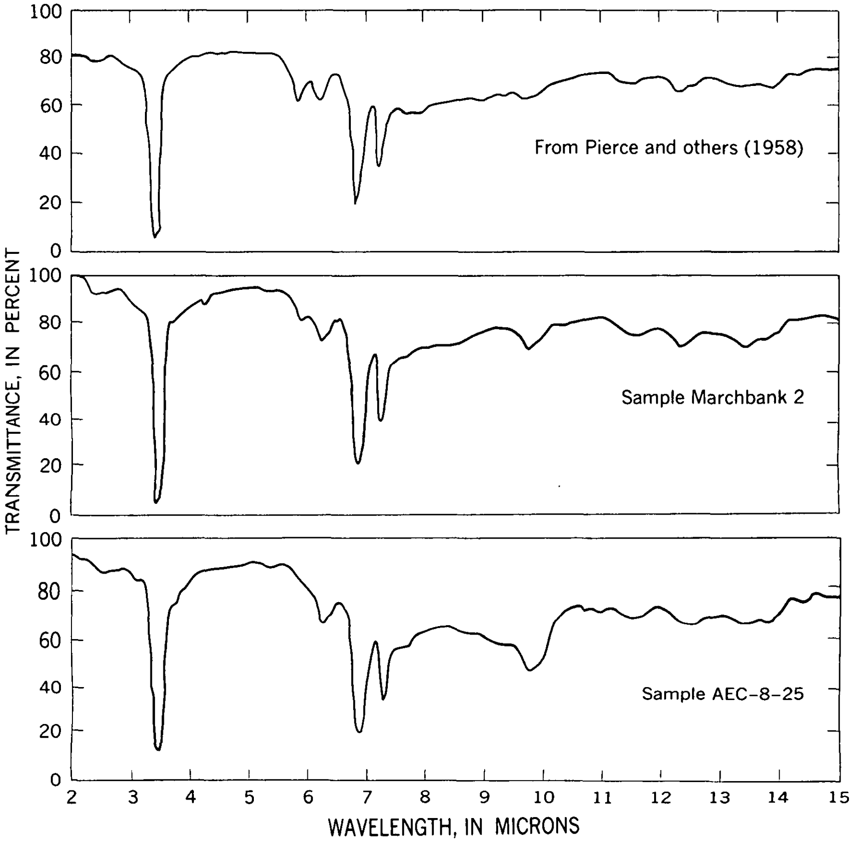

FIGURE 23.—Infrared spectra of oils extracted from the Moss Back Member, Temple Mountain area.

lite, but most commonly, asphaltite. The material is very similar in physical properties and in its relations to other minerals to the hydrocarbon or thucholite of the Witwatersrand, Africa (Liebenberg, 1955, p. 116–151; Davidson and Bowie, 1951), the thucholite or uraniferous hydrocarbon of Placerville, Colo., and the asphaltite of the Texas Panhandle (Pierce and others, 1956, p. 529–530). According to the classification of Abraham (1945, p. 60), the material is a pyrobitumen.

The term "asphaltite" is used throughout this report for the uranium-bearing carbonaceous material. Breger and Deul (1959) proposed that the asphaltite was derived from coaly materials rather than from petroleum. If this is so, then the term is inappropriate. We have concluded, however, that although the asphaltite may locally contain substances extracted from coals, it formed mainly from petroleum, and coaly substances were not essential to its formation. Perhaps in the future a better term will be proposed, but at present we prefer the term "asphaltite" because it has been widely used and it gives an impression of the appearance and, in our view, probable origin of the material.

PHYSICAL PROPERTIES

The asphaltite is a black, semilustrous to lustrous, rather hard (2–4) uraniferous substance having a semiconchoidal fracture; it is insoluble at normal temperatures and pressure in organic reagents and has distinctive optical properties. The specific gravity of 20 nodules reported in the literature ranges from 1.08 to 1.92 and averages about 1.44 (Breger and Deul, 1959, p. 145; Hausen, 1959, p. 31; Pierce and others, 1958, p. 197).

In polished section, the hardness of typical material is estimated to be about D, or at the upper (harder) end of Short's group of soft minerals (1940, p. 64–66). The asphaltite is commonly opaque, but in some ores part of the asphaltite is translucent (red brown) and in this way resembles the interstitial asphalt previously described. Hausen (1959, p. 27–29) found that the refractive index of asphaltite increases with the increasing opacity of the material; he determined a maximum index of 1.71 on almost opaque material.

The appearance of the asphaltite in polished section, especially under crossed nicols, is distinctive. In ordinary light the asphaltite is gray, somewhat darker than sphalerite, and at high magnifications ($> \times 400$) it may show two phases of contrasting shades. Under crossed nicols the asphaltite is slightly to moderately anisotropic and shows faint brownish colors. The anisotropism shows distinct banding and mottling, and, in places, the pattern is like that of irregular perthitic intergrowths. The mottling is most intense around blebs of uraninite. The anisotropism, color, and opacity distinguish typical asphaltite from all other components of the ores and seem to duplicate almost exactly those of thucholites studied by Davidson and Bowie (1951) and by Liebenberg (1955) who also noted more intense mottling in Witwatersrand thucholites occurring near uraninite.

OCCURRENCE AND MINERAL RELATIONS

The asphaltite is mainly confined to the uranium deposits of the Temple Mountain and Flat Top areas. In these places it occurs in several ways: it is found as nodules of various sizes, as interstitial fillings, and as massive replacements along bedding planes and the contacts of ore rolls. The amount of replacement by the asphaltite varies from slight but consistent corrosion of sand grains, through virtually complete replacement of local areas in the nodules (fig. 17, lower photo), to nearly complete replacement of the rocks in conformable layers and in rolls. Asphaltite veins and blebs (fig. 28, lower photo) of probable replacement origin are found in coalified or silicified logs, and nodules and veinlike masses of asphaltite occur along fractures in the Vanadium King 5 mine. All types of occurrences—interstitial, nodular, and massive replacements—can be found in a single ore body, but the occurrence is seemingly influenced to some extent by the type of rock. Nodules, for example, are most abundant in conglomeratic sandstones, and interstitial asphaltites are most common in fine-grained well-sorted sandstones. Asphaltite nodules in small quantities also occur in the mudstones and mudstone conglomerates which cap the ore-bearing sandstones.

Liesegang-like layers of asphaltite paralleling roll contacts were observed in the Camp Bird 7 and the Calyx 8 mines; the layers are 1–3 inches thick and are separated by layers of unmineralized sandstone of about the same thickness. Similar Liesegang phenomena were reported near roll contacts from other Colorado Plateau ores by Fischer (1942).

The mineralized rock impregnated with the interstitial asphaltite is black and is tightly cemented; in this respect it contrasts with rock containing interstitial asphalt, which is speckled gray and is friable.

As noted on preceding pages, the asphaltite-rich ore bodies locally have either sharp or gradational contacts. At sharp contacts the asphaltite ore is in contact with altered rocks containing sparse interstitial asphalt. In gradational zones, the asphaltite ore apparently grades into petroliferous rock, and the asphaltite itself seems to change to a dark-brown viscous oil. The apparent gradation takes place over distances ranging from less than 1 inch to 10 feet or more. Gradations over very small distances have been observed in the breccia ores in the collapse structure (p. 51) and in the Marchbank incline and Vanadium King 7 mine. A gradation over 10 feet or more is seen on the southwest side of ore body 5 in the Calyx 8 mine. In this ore body the grade of ore decreases southwestward from a sharp roll contact (figs. 11, 34); in the southwest, lower grade part of the ore body, asphaltite occurs as disseminations and small nodules concentrated along crossbeds and along the mudstone seams that bound the ore body. Farther to the southwest, the ore-bearing sandstone is petroliferous but contains scattered asphaltite blebs, and a few feet still farther the standstone contains only petroleum. The petroleum, like the asphaltite in the low-grade ore, is concentrated along certain crossbeds and mudstone seams. Southwest of the mining boundary the petroliferous sandstone contains about 0.015 percent uranium, and oil extracted from the sandstone is slightly uraniferous (0.0036 percent uranium; see sample 3, table 10).

A gradation between translucent asphalt and opaque asphaltite at Temple Mountain was observed by Hausen (1959, p. 29), who reported as follows:

> decrease in transmissibility of light * * * is accompanied by decrease in solubility, fusibility, plasticity, and by increase in hardness, brittleness, specific gravity, refractive index, reflectivity, and reflected anisotropism. These changes appear continuous rather than discontinuous, except for the change between liquid and solid phases, and correspond to increasing metal content.

COMPOSITION

Organic ultimate analyses show that the asphaltite is composed mainly of carbon, but that it also contains small amounts of oxygen, hydrogen, and sulfur, and less than 1 percent nitrogen. Results of several analyses (see table in next paragraph and table 11) indicate that the asphaltite averages about 23 percent nonvolatile ash and that uranium is the most abundant element in the ash.

Ultimate analyses, in percent, of Temple Mountain asphaltite from the Camp Bird 7 mine (furnished by A. P. Pierce of the U.S. Geological Survey) are as follows:

	Sample Ut-Tm-1n	*Sample Ut-Tm-2n*
C	61.01	59.95
H	3.58	4.01
N	.22	.12
S	2.40	5.03
O	9.23	8.59
Nonvolatile ash	22.33	22.07
Total	98.77	99.77

Carbon to hydrogen atomic ratios for samples Ut–Tm–1n and Ut–Tm–2n on an ash-free basis are 1:0.72 and 1:0.8, respectively. Other ratios, computed from eight partial ultimate analyses given by Breger and Deul (1959, p. 145), range from 1:0.76 to 1:1.12. These ratios show that most of the organic compounds in the asphaltite are either aromatic compounds, strongly dehydrogenated aliphatic compounds, or, more probably, include both. Dehydrogenated aliphatic compounds are indicated by aliphatic carbon X-ray diffraction halos found on Temple Mountain asphaltites by Pierce, Mytton, and Barnett (1958, p. 192 and table 1, samples 21 and 23).

Radiometric, chemical, and semiquantitative spectrographic analyses were made of six asphaltite-rich separates (table 11). The trace elements present in greatest concentrations in the nonvolatile part of the asphaltite are uranium, vanadium, arsenic, lead, and zinc; uranium is more abundant than the common elements aluminum and iron and in at least three samples is also more abundant than silicon. Smaller concentrations of cobalt, chromium, copper, nickel, yttrium, and selenium are also found in the asphaltite. These analyses are not entirely satisfactory since high concentrations of uranium (and vanadium) mask spectral lines of some elements. Moreover, these analyses probably do not truly represent the vanadium or selenium content of the asphaltite; for example, the content of selenium is high in sample 2 probably because the sample contains ferroselite, which was derived from the adjacent host sandstone; similarly, part of the vanadium in sample 5 is due probably to montroseite that is found in veins paralleling the asphaltite. The asphaltite probably contains an average of a few percent uranium, about 0.01 percent arsenic, less than 1 percent vanadium, and a few hundredths of a percent selenium. Some other spectrographically determined trace-element constituents and their average (arithmetic mean) concentrations in percent, are:

Mn, 0.009; Be, about 0.0001; Co, about 0.03; Cr, about 0.1; Cu, 0.008; Ni, about 0.007; Pb, 0.05; Y, 0.004; Zn, 0.1; and Zr, 0.01.

The infrared spectra of asphaltites are characterized by small absorption peaks and low transmittance of infrared radiation (fig. 24). Aromatic organic compounds are dominant, but minor absorptions at 3.5 and 6.9μ show that some aliphatic groups are present. Absorptions in the range 2.5–3.5μ show that hydroxyl (OH) and amine (NH) groups are present.

COALY MATERIALS

The coals of the district were derived from relatively coarse, fragmental woody material. They are found only in the Chinle Formation and are most abundant in the Moss Back Member, within which they are most abundant in the basal conglomeratic sandstone and in some mudstone-rich rocks. Small fragmental coalified branches occur in mudstone-rich zones and on bedding planes; finely divided coaly material is sparsely disseminated in the sandstones. Large fossil logs

TABLE 11.—*Analyses, in percent, of uraniferous asphaltite from the Moss Back Member of the Chinle Formation, Temple Mountain district*

[Semiquantitative spectrographic analyses: A single line of data for a sample gives analyses of unashed material; where 2 lines of data are given, upper line represents analyses of ash, lower line—calculated analyses of asphaltite (percent element in ash $\div \frac{100}{\text{percent ash}}$). Nl, not looked for. Ag, Ge, Mo, and Sn not detected; Na<0.1 in sample 1, not present or not looked for in other samples. Analysts: C. G. Angelo, eU; D. L. Ferguson and E. J. Fennelly, ash, U, and V_2O_5; C. A. Horr, As and Se; C. S. Annell, N. M. Conklin, and J. C. Hamilton, spectrographic]

Sample	Field No.	Lab. No.	Description and location	Radiometric and chemical analyses					
				eU	U	V_2O_5	As	Se	Ash
1	SR-1BS-55	239505	Nodules, Calyx 8 mine	4.37	7.02	0.03	[1] 0.7000	0.040	Nl
2	AEC-8-29B	253454	Massive replacement ore, Calyx 8 mine	4.07	4.41	.53	.1200	.4400	24.81
3		288456	do	Nl	3.8	[1] .7	Nl	Nl	Nl
4	AEC-8-21	253455	do	4.1	5.69	.96	.1000	.001	19.19
5	NM-9-3	253459	Asphaltite veining silicified wood, North Mesa 9 mine.	7.6	7.96	10.56	.0120	.0015	26.53
6	Marchbank 1	288455	Massive replacement ore, Marchbank incline	Nl	1.7	[1] 1.5	Nl	Nl	Nl

Semiquantitative spectrographic analyses

Sample	Si	Al	Fe	Mg	Mn	Be	Co	Cr	Cu	Ni	Pb	Y	Zn	Zr
1	.7	.3	0.15	0.003	0.001	Trace	<0.005	0.015	0.03	0.0007	.015	0.007	0	0.007
2	>10	7	7	.07	.03	.0003	.15	1.5	.03	.07	.3	.015	.7	.03
	>2.4	1.7	1.7	.017	.007	.00007	.04	.4	.007	.02	.07	.004	.2	.007
3	.3	.3	.3	.015	.007	0	.07	.15	.007	.007	.07	.003	0	.03
4	>10	3	1.5	.15	.07	.0015	.07	.015	.007	.03	.3	.015	.3	.03
	>1.9	.6	.3	.03	.006	.0003	.01	.003	.001	.006	.06	.003	.06	.006
5	.3	.7	1.5	.015	.07	.0007	Nl	.003	.007	.015	.3	.007	1.5	.03
	.08	.2	.4	.004	.02	.0002	------	.0008	.002	.004	.08	.002	.4	.008
6	1.5	.7	.3	.015	.015	0	<.01	.007	.003	.007	.003	.007	.07	.007

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[1] Semiquantitative spectrographic determination.

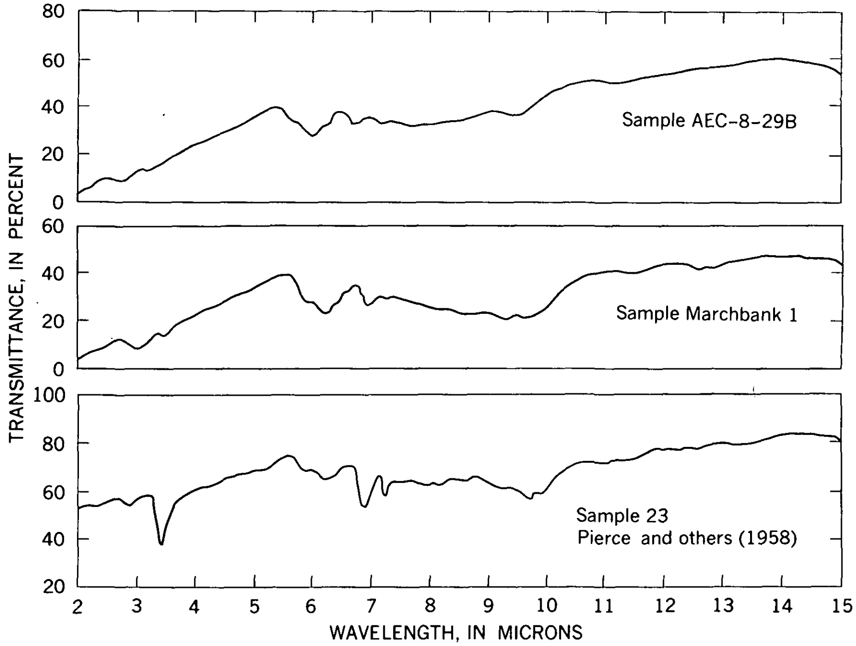


FIGURE 24.—Infrared spectra of asphaltites from uranium deposits in the Moss Back Member, Temple Mountain area.

occur in the basal conglomeratic sandstone. Typically the inner part of a large log is silicified, and this silicified zone is rimmed with coal.

Much of the coaly material is lustrous, almost black, and breaks with a semiconchoidal fracture; it evidently was derived from woody material and is classifiable as vitrain or anthraxylon (Marshall, 1955, table 1 and p. 780–785). Most of the vitrain has a layered structure (fig. 28); some is virtually structureless. Locally the layered type has been deformed into tight microscopic folds. Structureless vitrain fills fractures in coal and in adjacent rocks and presumably is hardened organic material squeezed from the coals during compaction.

The coals contain a considerable variety of metallic minerals, of which pyrite is the most abundant. Sphalerite is common and is found in both ore and barren zones. Many of the coalified logs in the mines are coated with corvusite, which suggests the presence of primary vanadium minerals in the logs.

In contrast to the coals of many other areas on the Colorado Plateau, coals of the Temple Mountain district contain relatively small amounts of uranium. The only notably radioactive coals are those that are veined or partly replaced by asphaltite.

Table 12 summarizes the results of inorganic analyses of three vitrain concentrates. Of the trace elements, zinc is present in the

TABLE 12.—*Analyses, in percent, of vitrain, Temple Mountain district*

[Semiquantitative spectrograhic analyses: Upper line of figures gives analyses of vitrain ash, lower line gives calculated analyses of vitrain $\left(\text{percent element in ash} \div \frac{100}{\text{percent ash}}\right)$. M, major constituent (> 10 percent). Ge was looked for but not found; Ca and Na were not looked for. Analysts: C. G. Angelo, eU; D. L. Ferguson, ash, U, and V_2O_5; C. A. Horr, As and Se; C. S. Annell, spectrographic]

Sample	Field No.	Lab No.	Location	Radiometric and chemical analyses						
				eU	U	U in ash	V_2O_5	As	Se	Ash
1	AEC-8-16	253461	Mudstone immediately below ore, Calyx 8 mine	0.041	0.048	0.540	2.52	0.0110	0.001	8.92
2	AEC-8-20	253462	Area of slightly mineralized rocks, Calyx 8 mine	.001	.0048	.053	.10	.007	.002	8.96
3	NM-1-2	253463	Area of slightly mineralized rocks, North Mesa 1 mine.	.002	.0021	.115	.29	.003	.0004	1.92

Sample	Semiquantitative spectrographic analyses															
	Si	Al	Fe	Mg	Mn	Ag	Be	Co	Cr	Cu	Mo	Ni	Pb	Y	Zn	Zr
1	1.5 .15	1.5 .15	7 .6	0.3 .03	0.03 .003	0.0003 .00003	0.0003 .00003	0.03 .003	0.015 .0015	0.03 .003	0.03 .003	0.03 .003	0.07 .006	0.007 .0006	7 .6	0.07 .006
2	M >.9	3 .3	3 .3	.7 .06	.07 .006	.0003 .00003	.0003 .00003	.015 .0015	.003 .0003	.03 .003	.07 .006	.03 .003	.015 .0015	.015 .0015	3 .3	.3 .03
3	M >.19	3 .06	7 .15	.7 .015	.03 .0006	.0007 .000015	.0015 .00003	.03 .0006	.015 .0003	.15 .003	.15 .003	.07 .0015	.15 .003	.03 .0006	7 .15	1.5 .03

highest concentrations; copper, molybdenum, lead, nickel, and zirconium are present in lesser amounts.

ORIGIN

Infrared spectra, chemical composition, and trace-element content have been cited previously as evidence on the origin of the carbonaceous materials. Although these data are significant, they must be evaluated critically. Two interrelated factors have generally not been considered: (1) the composition and physical properties of asphaltite and other carbonaceous substances are not what they originally were, and, therefore, analyses are not representative of the substances as originally formed; and (2) the asphaltite is a derivative of another carbonaceous substance, and its composition should not be expected to be exactly the same as that of the parent material.

The suites of trace elements contained in the various carbonaceous materials are similar, but differences exist both in absolute concentrations and in relative amounts of trace elements present. In general, genetic relations between the various substances cannot be inferred from the trace-element data. Arsenic, beryllium, cobalt, chromium, copper, nickel, lead, vanadium, zinc, zirconium and possibly silver are trace elements present in petroleum, asphaltite, and vitrain. In contrast, tin is present in more than half of the oils but is not present in either coal or asphaltite; similarly, molybdenum is present in coals and very sparsely in oil, but it was not detected in the asphaltite. Some elements present in all three carbonaceous substances are highly enriched in only one. Zirconium, for example, is more abundant in coal than in either oil or asphaltite, and arsenic, cobalt, chromium, copper, nickel, and lead are present in larger concentrations in asphaltite than in either coal or oil.

The trace-element content of ash from an asphaltite nodule from the Rex 2 (Vanadium King 1) mine was discussed by Breger and Deul (1959, p. 145, 146, table 7). The ash contains 10 different rare-earth elements and apparently does not contain sodium. Breger and Deul pointed out that petroleum ash does not generally contain as many of the rare earths and does generally contain sodium; on these bases they concluded that the nodule had a nonpetroliferous origin. Several factors suggest that this is not necessarily a valid conclusion. The composition of the nodule is atypical, on the basis of analyses of both asphaltite and asphaltite-rich ores (tables 3 and 11). Asphaltite nodules rich in rare earths are found in uranium deposits in other parts of the San Rafael Swell. The deposits themselves are anomalously rich in rare earths, which probably were incorporated in the asphaltite when the deposits formed and were not derived from the parent carbonaceous material. In addition, the apparent absence of sodium is inconclusive as evidence of origin because in semiquantitative spectrographic analyses sodium commonly goes undetected owing to its lack of sensitivity in the wavelength range generally used. Sodium is present in at least one of the asphaltites whose analyses are shown in table 11.

Infrared analyses do not conclusively relate the asphaltite to either coal or petroleum. All three types of carbonaceous substances contain both aliphatic and aromatic organic compounds, but the coal and asphaltite have smaller amounts of aliphatic groups, more aromatic groups, and more hydroxyl. In general, the shapes of asphaltite spectra are more similar to those of coals (vitrain) than to those of petroleum (fig. 25). Breger and Deul (1959, p. 143, 144, figs. 44 and 45) suggested that the sparsity of aliphatic groups and the presence of hydroxyl in asphaltite and organic material extracted from the asphaltite show that the asphaltite was derived from coal. However, the CH, CH_2, and CH_3 groups, which give rise to the aliphatic absorptions, are expected to be sparse owing to the presence of uranium and regardless of the origin of the asphaltite. Most of the energy produced by the decay of uranium is given off by alpha particles, and it has been shown that alpha-particle bombardment of organic sub-

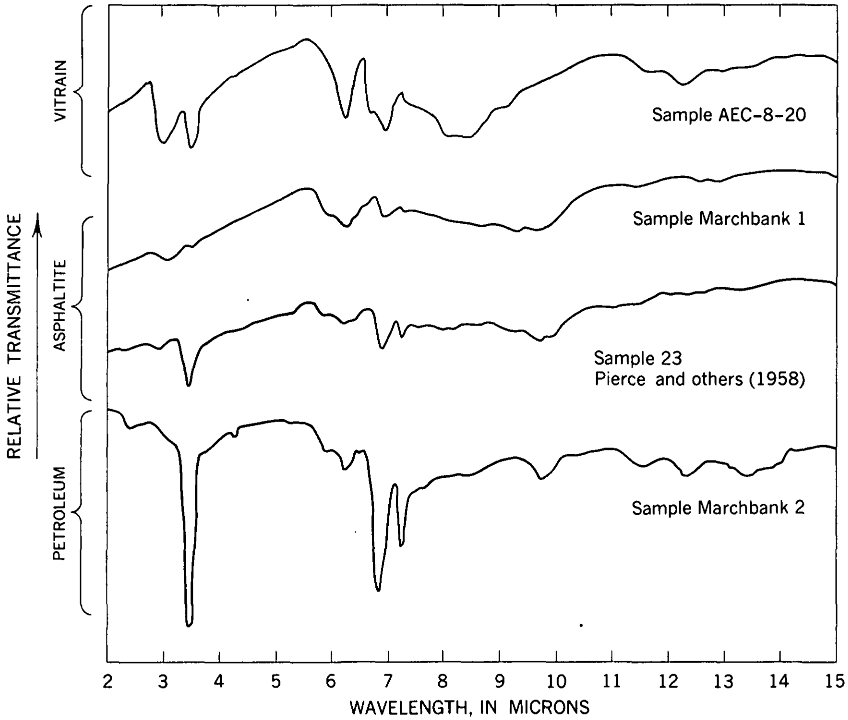


FIGURE 25.—Infrared spectra of vitrain, asphaltite, and petroleum from Moss Back Member, Temple Mountain area.

stances causes dehydrogenation and loss of light hydrocarbons (Sheppard and Whitehead, 1946; Breger, 1948). Pierce, Mytton, and Barnett (1958, fig. 1, p. 195–196) also determined that the hydrogen in asphaltites and related substances decreases in direct proportion to the dosage of radiation that the materials have received. The effects of different amounts of radiation on aliphatic groups are perhaps illustrated by the difference in spectral patterns of samples Marchbank 1, AEC–8–29B, and 23 (fig. 24). Sample AEC–8–29B contains about 3.8 percent uranium and shows no well-defined absorptions in any region; Marchbank 1, which contains 1.7 percent uranium, shows minor aliphatic absorptions; sample 23, which contains only 0.5 percent uranium, shows well-defined aliphatic absorptions, and its pattern is perhaps more similar to that of petroleum than that of the vitrain (fig. 25).

In addition to causing hydrogen deficiency in the asphaltites, alpha radiation possibly contributes to their hydroxyl and oxygen content. Analysis of asphaltites from Temple Mountain and other parts of the San Rafael Swell (Pierce and others, 1958, table 1, samples 16–23) shows that oxygen content is inversely related to hydrogen content and directly related to radioactivity of the asphaltite (fig. 26). This correlation may be due directly to the alpha radiation. Unsatisfied valences result from removal of hydrogen from an aliphatic chain by radiation; these valences can be satisfied either if double carbon bonds are formed within the chain or if an atom or group—for example, oxygen or hydroxyl—fills the position or positions vacated by hydrogen.

SECONDARY MINERALS

A considerable variety of secondary minerals containing high-valent uranium and vanadium is found in the district. Carnotite or tyuyamunite are important constituents in outcropping or near-surface ores of such mines as the Camp Bird 12 group ("South workings"). Most of the secondary uranium and vanadium minerals, however, are not abundant. Secondary uranium or vanadium minerals reported (Hess, 1933; F. M. Murphy, written commun., 1944; Gruner and Gardiner, 1952; Hausen, 1959) include torbernite, metazeunerite, uvanite, rauvite, bayleyite, bassetite, corvusite, metahewettite, pintadoite, pascoite, schroeckingerite, and zippieite. Three secondary minerals—abernathyite (Thompson and others, 1956), rauvite, and uvanite (Hess and Schaller, 1914; Hess, 1925, p. 68–70)—were discovered in the Temple Mountain district. Certain of the secondary minerals, specifically corvusite and pascoite, are fairly common as thin coatings on recently exposed black ores; others—rauvite, uvanite, and meta-

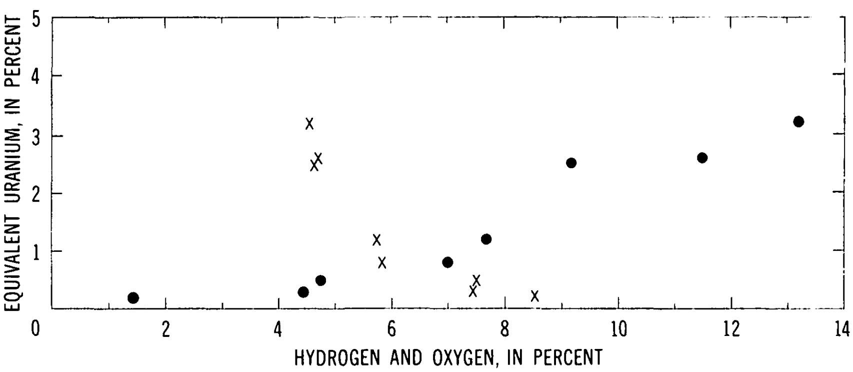


FIGURE 26.—Correlation of hydrogen (×) and oxygen (●) with equivalent uranium in asphaltites from the San Rafael Swell. Data from Pierce, Mytton, and Barnett (1958, table 1, samples 16–23); hydrogen and oxygen calculated to ash-free basis.

hewettite—are most common in the vanadiferous more typically oxidized ores of the Wingate Sandstone. The copper uranyl minerals torbernite and metazeneurite are found as thin coatings on ores at the Vagabond mine in the Wingate Sandstone and at several places in the Flopover, but on the Calyx Bench they were noted only in the Vanadium King 1 mine. Corvusite also is common in thin coatings on fractures and in this mode of occurrence appears to be secondary. At Flat Top, however, some corvusite occurs in apparently unoxidized ore as seams as much as half an inch thick paralleling the bedding. This corvusite probably is primary or was formed by oxidation in place of a mineral containing lower valent vanadium.

Secondary compounds of other metals are local constituents of oxidized ores. Hematite, limonite, jarosite, and alunite and other sulfates are locally common in the district. The arsenic-bearing minerals scorodite and pitticite (M. E. Thompson, written commun., 1956) are found in the Temple Mountain collapse and probably occur in others collapses; locally, they impart yellow to yellow-brown colors to the collapsed rocks. Orpiment and realgar coat rock containing native arsenic at the Camp Bird 7 mine and have also been reported from drill core in the Temple Mountain collapse (Keys and White, 1956, p. 290, 291).

The vanadium mineral pascoite and the rare cobalt selenite, cobaltomenite (J. R. Houston, oral commun., 1956), coat sandstone near asphaltite ore bodies in the Moss Back. In altered rocks surrounding ore these minerals indicate concentrations of other vanadium and selenium minerals, which are unoxidized, very fine grained, and not otherwise easily visible. For this reason, pascoite, cobaltomenite, and chromium-bearing silicates are useful in mapping ore boundaries.

PARAGENESIS

The ore deposits are composed chiefly of asphaltite but also contain small amounts of disseminated metallic minerals. A distinctive suite of minerals—namely, uraninite, montroseite, sphalerite, pyrite, and ferroselite—comprises the bulk of the metallic minerals associated with asphaltite. Microscopic relations suggest that most asphaltite formed later than most of the associated metallic minerals. The association everywhere of asphaltite with uraninite, montroseite, and other components of the suite suggests, however, that the asphaltite and the associated metallic minerals were introduced by the same solutions and that the time interval between deposition of metallic minerals and asphaltite was very short.

Small amounts of pyrite, sphalerite, and other metallic minerals formed in the rocks before the main period of uranium mineralization. Petroleum was emplaced before the main mineralization, but since its introduction it has migrated locally into the Moss Back Member and other strata.

In most places the asphaltite embays, veins, and includes apparently brecciated fragments of the associated suite of metallic minerals, and it is therefore assumed to be younger than the metallic minerals. Uraninite, in particular, is common in irregular grains, which appear to be floating in asphaltite (fig. 18). In a few places very small amounts of pyrite and other metallic minerals are younger than asphaltite. Pyrite, sphalerite, and the less common chalcopyrite, in very small amounts, apparently replace asphaltite along its boundaries with detrital minerals (fig. 27). Pyrite and an extremely fine grained gray mineral, possibly uraninite, also in very small amounts, locally occur as crystals and blebs within the asphaltite and appear to have formed in place by replacement or exsolution or perhaps in an oil-water emulsion. The uraninite(?) blebs in particular resemble chalcopyrite blebs formed by exsolution in sphalerite.

The coals contained in the uranium deposits and nearby barren rocks have recorded structural activity by their mode of deformation and show two and possibly three periods of mineralization. In the early period, pyrite and some marcasite replaced cell walls and were deposited in undeformed cells. Deposition of pyrite was followed by a period during which the coals were deformed, pyritic areas were fractured, and coaly material flowed into the fractures engulfing pyritic cells and groups of cells (fig. 28 upper photo.). At this time a layered structure was formed or accentuated in some of the vitrain (fig. 28, lower photo.), and blebs of sphalerite may have been deposited along the boundaries between the layers.

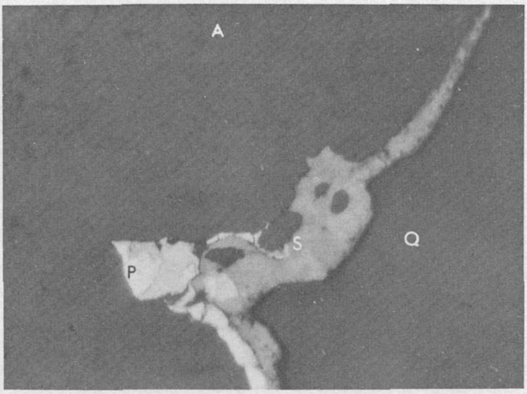


FIGURE 37.—Photomicrograph of ore, showing sphalerite (S) and other sulfides (P, pyrite and chalcopyrite) on quartz-asphaltite (Q–A) boundary. × 455.

Formation of ore followed hardening of the coal; evidence for this is that the later deformation of coals before or during the period of ore formation resulted in fracturing rather than flowage of coaly materials. Uraninite, asphaltite, montroseite, ferroselite, pyrite, a second generation of sphalerite, and rarely other minerals formed during the main period of ore deposition and occur in the coals in crosscutting vein or replacement zones. Some rocks show both generations of sphalerite in one polished section (fig. 29). Figure 29 shows bands of the early sphalerite paralleling nearly undeformed woody structure. The early sphalerite is veined by pyrite, which in turn formed before a veinlet containing both sphalerite and montroseite.

The paragenetic sequence of asphaltite and metallic minerals is summarized diagrammatically in figure 30. The minerals indicated on the left side of the dividing line were deposited while the coal could deform plastically; those indicated on the right side were deposited after the coal was hard enough that it fractured when deformed. The amount of time represented in the diagram is speculative, but the earliest minerals probably formed during diagenesis. The sphalerite shown as deposited during the early period may have formed at the time of the regional alteration of the Temple Mountain and Monitor Butte Members of the Chinle; during that alteration period sphalerite formed, as well as small amounts of pyrite, chalcopyrite, and galena, in bedded chert veins in those members.

The gangue minerals of the deposits are chiefly quartz, feldspar, calcite, dolomite, and clay minerals. The quartz, feldspar, and some of the clay minerals are detrital components of the rocks. Carbonates, quartz in subhedral overgrowths, and some clay minerals were formed during diagenesis or later. Calcite in cement and quartz in subhedral

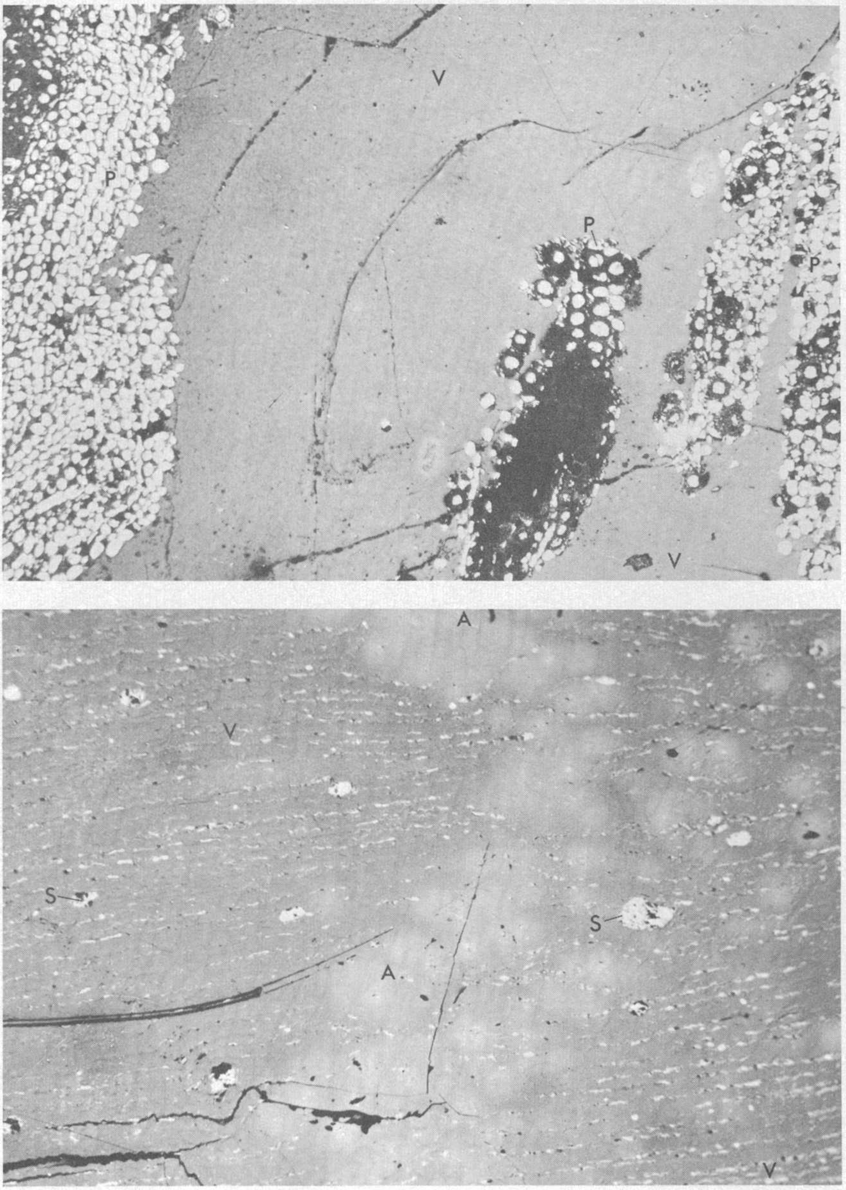
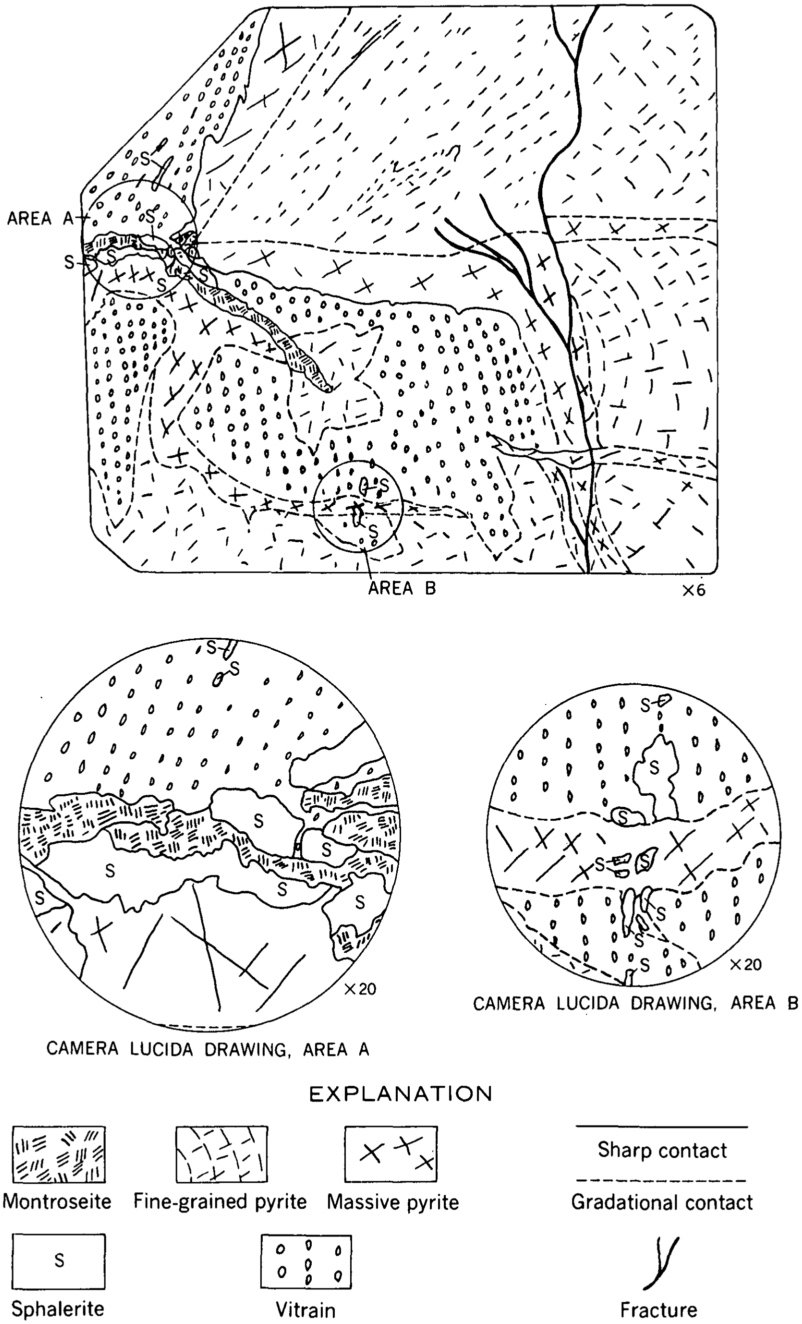


FIGURE 28.—Photomicrographs of ore, showing cell-structure pyrite (P) in vitrain (V), × 55 (upper photo.), and asphaltite (A) zone crosscutting sphalerite-bearing (S) vitrain (V), × 55 (lower photo.).



CAMERA LUCIDA DRAWING, AREA A

CAMERA LUCIDA DRAWING, AREA B

FIGURE 29.—Sketch and camera-lucida drawings of polished section of coalified and pyritized wood showing two generations of sphalerite.

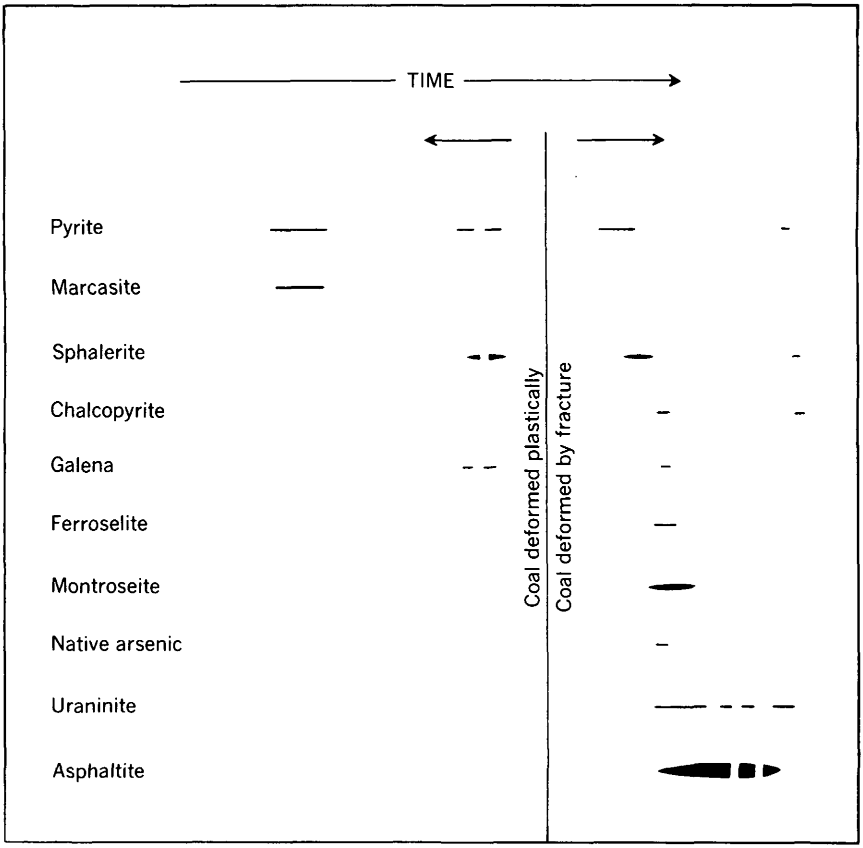


FIGURE 30.—Paragenetic sequence of asphaltite and metallic minerals relative to the time of deformation of coaly material. Dashed lines show inferred relations. Thickness of lines indicates relative amounts deposited.

overgrowths are considered to be diagenetic because they are widely distributed in the San Rafael Swell. Kaolinite and mica clays are likewise widespread. They are partly syngenetic and partly diagenetic, but because near the collapse structures they are more abundant, more coarsely crystalline, and replace detrital minerals, some clay minerals probably formed or recrystallized during the alteration related to the collapse structures. Other gangue minerals, specifically dolomite, some relatively coarse mica clays, and quartz in euhedral overgrowths, are spatially associated with ore and probably formed slightly before or concurrently with ore deposits. The formation of the chromiferous and vanadiferous green and gray mudstones, largely by alteration of preexisting rock units, is also regarded as being nearly contemporaneous with the formation of the ore deposits.

The time of emplacement of petroleum is an additional paragenetic problem. Most data suggest that petroleum was in the rocks before ore deposition. The rocks at Temple Mountain are inferred to have been petroliferous before the formation of collapse structures, owing to the presence of blocks of petroliferous sandstone in breccias in the collapse structures and displacement of petroliferous zones by small faults in the collapses. Some of the faults that displaced and controlled alteration of petroliferous zones subsequently controlled the formation of asphaltite-rich ore pipes. Away from the collapses, blebs of interstitial asphalt occur in altered rocks; they are inferred to be a residue of petroleum displaced during alteration.

METAL ZONING

The concentrations of certain extrinsic elements vary systematically in the Temple Mountain area and, also in individual ore bodies. The pattern of these variations in concentration is termed "metal zoning." The variations have been studied both by means of chemical and spectrographic analyses and by detailed mapping of mineral zones in ore bodies.

Vanadium, arsenic, selenium, copper, lead, and zinc all show zonal relations in the Temple Mountain area. The pattern of zoning is different, however, for different elements or groups of elements. Vanadium and arsenic vary in the same manner, selenium shows a different distribution, and copper, lead, and zinc, which locally correlate with vanadium, generally show a more complex pattern than either vanadium (and arsenic) or selenium.

The zoning of vanadium is best shown by contouring $V_2O_5:U_3O_8$ ratios computed from the production data. The deposits whose ratios are 4:1 or more are found only at Temple Mountain; eastward and southward the ratios decrease to less than 2.5:1 (fig. 31). The vanadium-rich deposits are near the Temple Mountain collapse structure. This could be fortuitous, the collapse being in a belt of vanadium-rich ores, or it could be the result of zoning around the collapse. The latter interpretation is more probable, because deposits at Flat Top, which are also near a collapse structure, are similar in size and vanadium content to those of North Temple Mountain.

On first analysis the occurrence of highly vanadiferous ores in the Wingate Sandstone near the Temple Mountain collapse seems to bear out the hypothesis of zoning of vanadium around the collapse. However, the deposits in the Wingate strongly resemble the highly vanadiferous ores found in clean well-sorted sandstones at Rifle and at Placerville, Colo., and their vanadiferous nature may reflect lithologic control rather than proximity to the collapse structure.

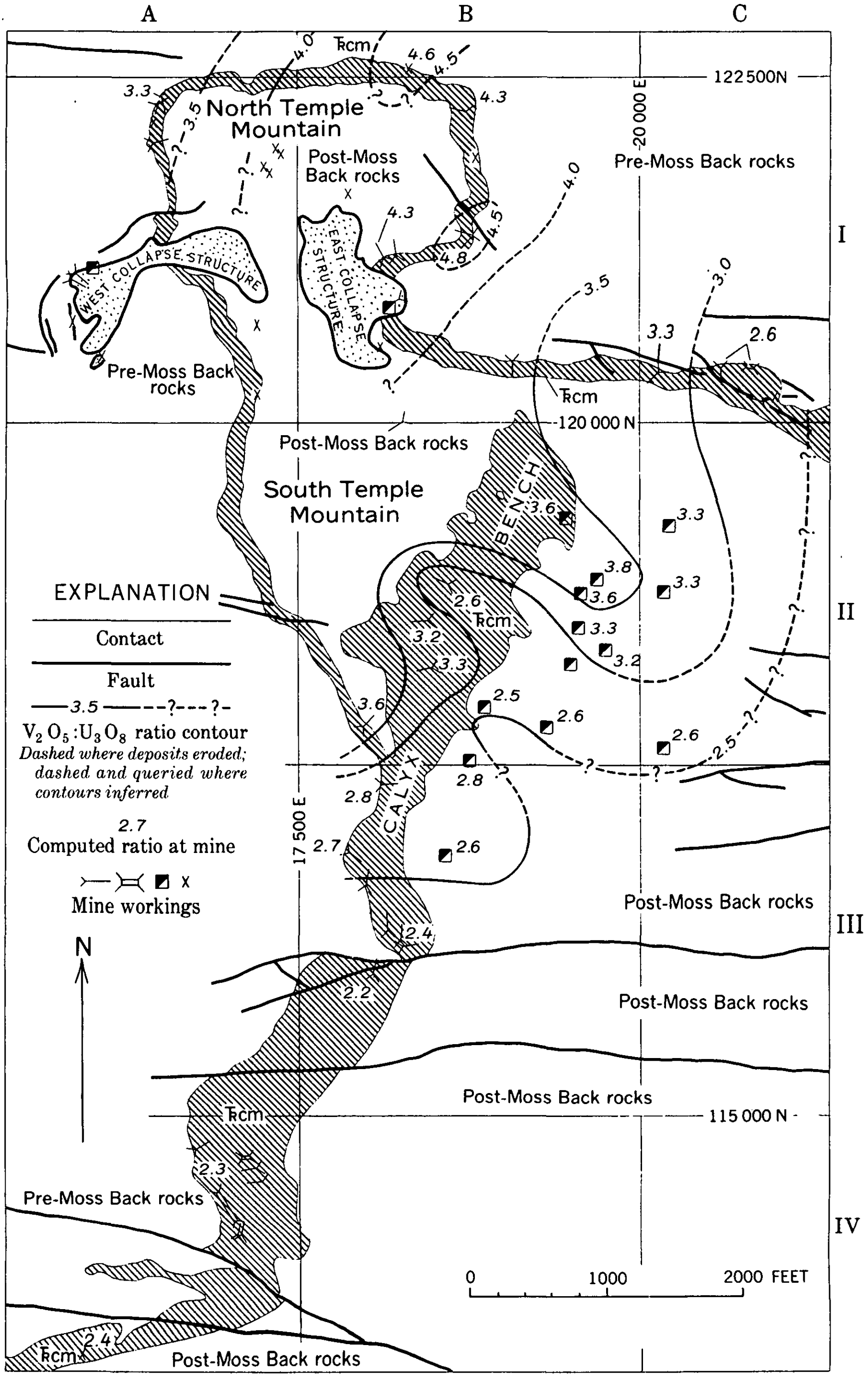


FIGURE 31.—Zoning in V_2O_5 : U_3O_8 ratio in uranium deposits in the Moss Back Member, Temple Mountain area. Ratios from ore-production data, 1948–56.

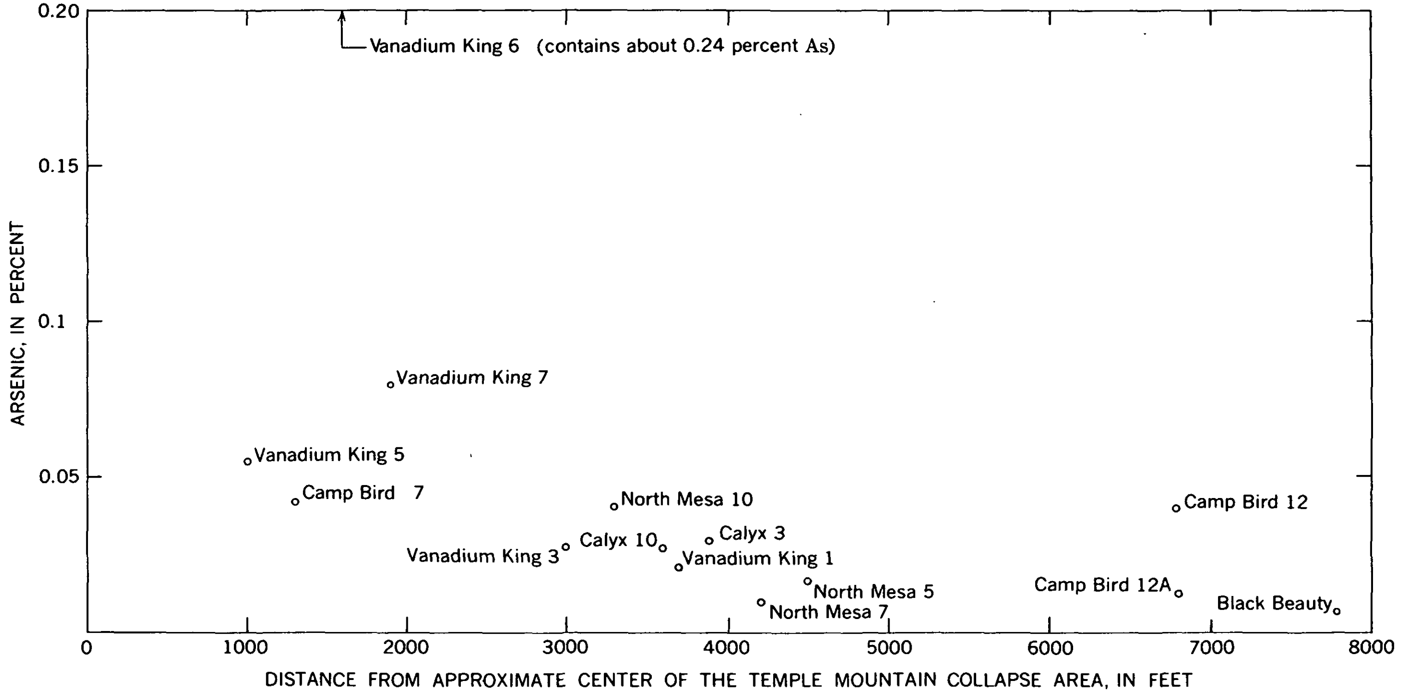


FIGURE 32.—Arsenic content of ores (table 3) in the Moss Back Member in relation to distance from the Temple Mountain collapse area.

Data on arsenic, although not as complete as those on vanadium, also suggest zoning around the Temple Mountain collapse. Ore deposits in the collapse contain native arsenic as well as orpiment and realgar. In zones of slightly mineralized rock, arsenic occurs as the minerals pitticite and scorodite. Arsenic minerals have also been found in deposits in the Moss Back Member near the collapse on North Temple Mountain, but they have not been identified from ores of the Temple Mountain mineral belt. If the east edge of the West collapse is assumed to be the center of the collapse area, the arsenic content of the ores apparently is inversely related to distance from the collapse (fig. 32).

In contrast to arsenic and vanadium, selenium is more abundant in the ore deposits on the Calyx Bench than in those on North Temple Mountain. South of the Calyx Bench, selenium seems to decrease as vanadium and arsenic decreases. Data from table 3 suggest that the amounts of selenium and arsenic vary in the same manner where these elements are each present in concentrations of less than 250 ppm, but where arsenic is present in concentrations greater than 250 ppm the two elements tend to vary inversely (fig. 33). Although the cause of this change in correlation is not known, it probably is also the cause of the difference in zonal distribution of selenium and arsenic.

In general, copper, lead, and zinc vary in the same manner. High concentrations of these three elements are locally found in vanadium- and arsenic-rich deposits on North Temple Mountain; this suggests some correlation between the two groups. But high concentrations of copper, lead, and zinc also occur in less vanadiferous deposits of the North Mesa group on the south part of the Calyx Bench. High concentrations of lead and zinc, in particular, may be due to the fact that much of the ore occurs in the basal conglomerates of the Moss Back—particularly in the North Mesa 2 and North Mesa 9 mines. These conglomerates contain more coal than do the stratigraphically higher sandstones, and the coals, in turn, contain noticeable concentrations of sphalerite and galena.

In individual ore bodies the distribution of chromium, selenium, vanadium, and other elements—including some of the common rock-forming elements—varies systematically with the distribution of uranium. The results of sampling across ore body 5 (pl. 4) in Calyx 8 mine show some of the variations in metal content. Some of the analytical results are shown graphically in figure 34; most are included in table 13. The rocks sampled are all from about the same stratigraphic position in one rock unit—a fine- to medium-grained, cross-bedded, quartzose sandstone of the massive sandstone facies of the Moss Back Member. From west to east the sandstone in the samples is (1) barren and petroliferous, (2) slightly mineralized with uranif-

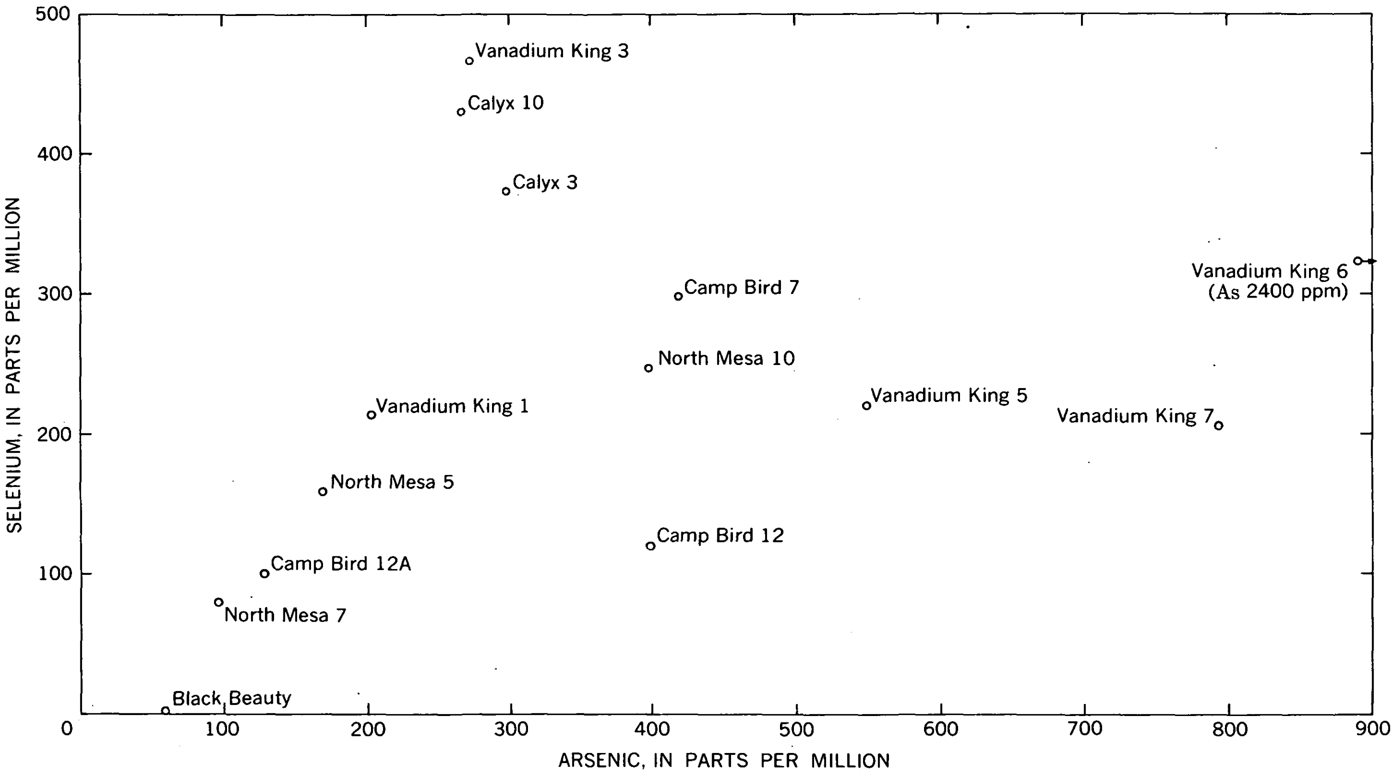


FIGURE 33.—Correlation of arsenic and selenium (table 3) contents of ore deposits in the Moss Back Member, Temple Mountain area.

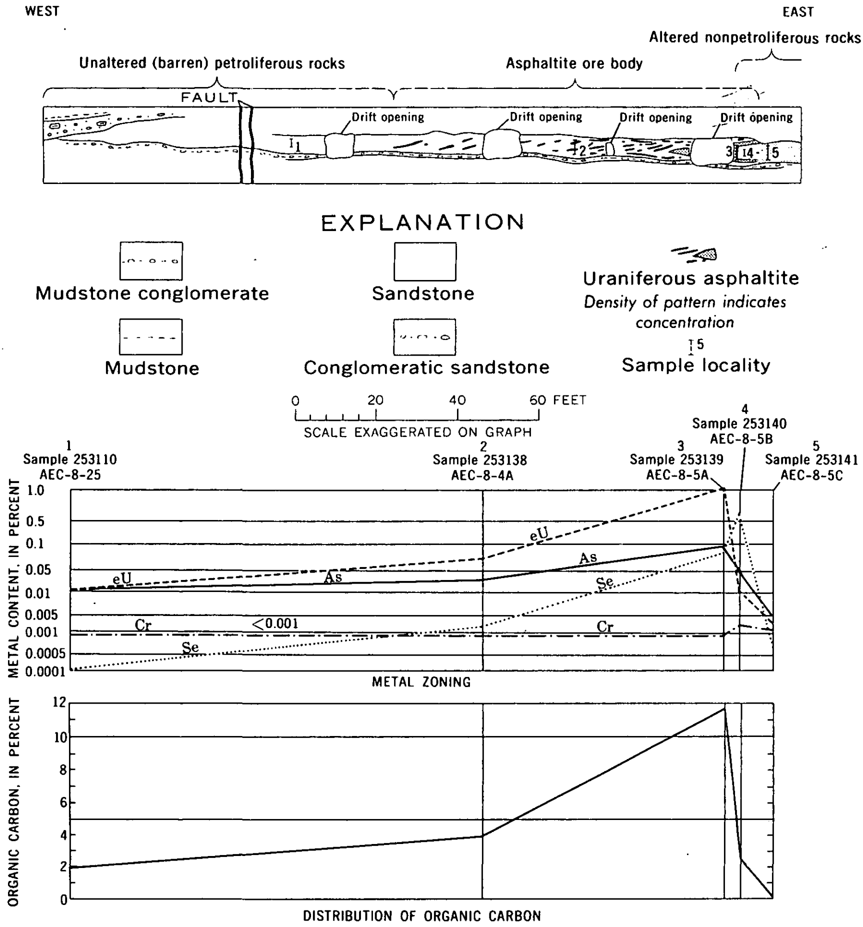


FIGURE 34.—Metal zoning and distribution of organic carbon across ore body 5, Moss Back Member, Calyx 8 mine. Carbon analyses by I. C. Frost, 1960.

erous asphaltite, (3) highly mineralized with uraniferous asphaltite, and (4) altered and nonpetroliferous but containing interstitial asphalt. Two samples were taken of the altered rocks—one was immediately adjacent to a sharp roll contact of high-grade ore; the other was about 3 feet from the ore contact. Plotted on a graph (fig. 34), the data show that west of the roll, toward unaltered barren rock, the concentrations of the metals in the ore decrease gradually; east of the roll, however, toward altered rock, the concentration of uranium drops sharply, but the concentrations of selenium and, to a slight degree, chromium rise and are higher in altered rocks than in ore. The analyses (table 13) show that iron, cobalt, copper, nickel, and zinc are also enriched next to ore, in the zone richest in selenium. Arsenic and possibly lead, in contrast vary with uranium. Magnesium and calcium are generally present in higher concentrations in both altered and barren rocks than they are in ore.

TABLE 13.—*Chemical composition, in percent, of samples*[1] *taken across ore body 5, Calyx 8 mine*

[M, major constituent (>10 percent). Analyses are semiquantitative spectrographic unless noted as follows: (c), chemical; (r), radiometric. Analysts: C. G. Angelo, eU; Claude Huffman, Jr., As; Wayne Mountjoy, Cr; G. T. Burrow, Se; H. H. Lipp, Zn; Joseph Haffty, spectrographic]

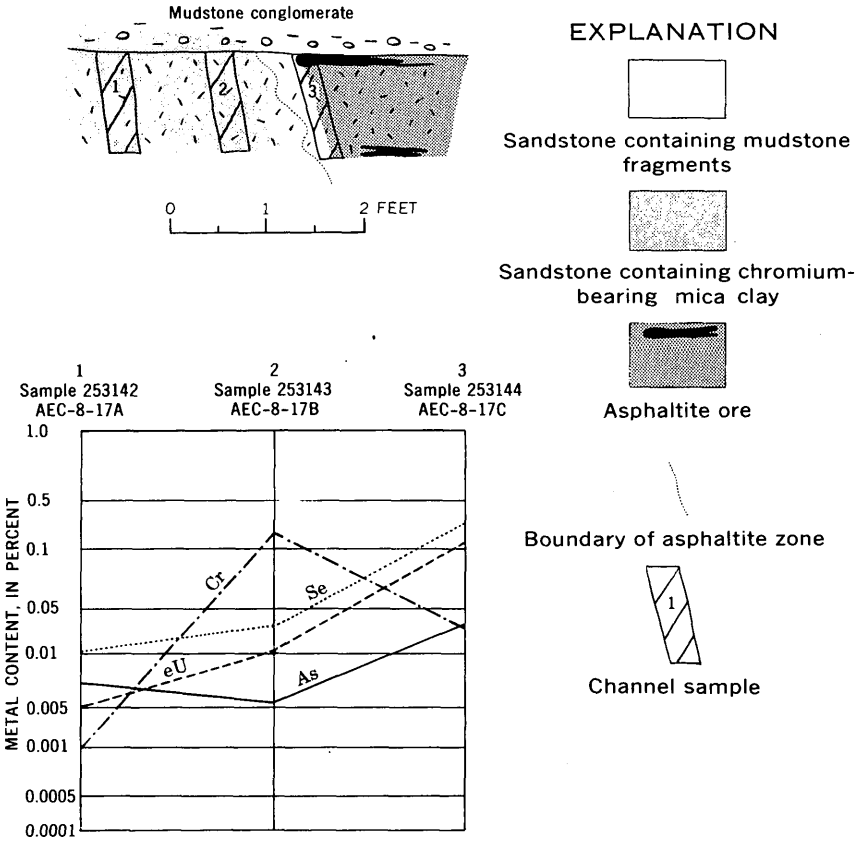
	1	*2*	*3*	*4*	*5*
eU	0.015(r)	0.075(r)	1.2(r)	0.015(r)	0.002(r)
V	.015	.3	.7	.07	.003
Se	.0001(c)	.0025(c)	.0870(c)	.630(c)	.0006(c)
As	.010(c)	.0315(c)	.0980(c)	.0430(c)	.0045(c)
Si	M	M	M	M	M
Al	1.5	1.5	1.5	.7	.7
Fe	3	.7	.7	1.5	.15
Mg	1.5	.03	.07	.015	.3
Ca	3.0	.07	.3	.07	M
Na	.07	.07	.15	0	.07
K	0	0	0	0	0
Ti	.03	.03	.015	.03	.07
Mn	.03	.003	.007	.003	.07
Ag	0	0	.000015	.000015	.00003
Co	.0007	.003	.03	.15	.003
Cr	.0007	<.001(c)	<.001(c)	.003(c)	.002(c)
Cu	.007	.003	.007	.07	.03
Ni	.0015	.007	.07	.15	.003
Pb	.003	.0015	.015	<.001	<.001
Y	Trace	.003	.003	0	.003
Zn	0	.015	.0130(c)	.0190(c)	.0005(c)

[1] Samples on main haulageway through 119,400 N. 018,400 E.

Field Nos.: (*1*) AEC-8-25, (*2*) AEC-8-4A, (*3*) AEC-8-5A, (*4*) AEC-8-5B, (*5*) AEC-8-5C.
Lab. Nos.: (*1*) 253110, (*2*) 253138, (*3*) 253139, (*4*) 253140, (*5*) 253141.

More detailed sampling across a small body of asphaltite ore shows a somewhat different zonal picture (fig. 35). This ore body is in fine-grained sandstone, capped by mudstone conglomerate, and contains scattered quartzose pebbles and mudstone seams and galls. As in ore body 5, chromium is more abundant outside of ore than in it (fig. 35), and copper and zinc are probably slightly more abundant in the chromiferous rocks than in the ore. In contrast, in this suite of samples, cobalt and nickel are more enriched in ore than in the adjacent rocks; selenium is also more abundant in the ore than in the sampled altered rocks, although a cobaltomenite coating on the altered zone between the areas of samples 2 and 3 suggests that selenium may also be enriched in this zone.

Metal zoning adjacent to a tabular ore body in the Calyx 8 mine is inferred from zonal distribution of minerals observed in a wall exposure (fig. 36). A zone of asphaltite ore (part of the tabular ore body) is underlain first by altered sandstone containing dolomite nodules and second by altered sandstone containing chromium-bearing silicates; this suggests zonal enrichment of calcium, magnesium, and chromium peripheral to ore. The dolomite nodules are coated with



Other elements, in percent

	Sample 253142	*Sample 253143*	*Sample 253144*
Ag	0	0	Trace
Co	.003	.015	0.03
Cu	.03	.03	.015
Ni	.003	.015	.07
Pb	.0	.0015	.0015
Zn	.005	.010	.007

FIGURE 35.—Metal zoning across a small ore body, Moss Back Member, Calyx 8 mine. Analysts: C. G. Angelo, Claude Huffman, Jr., Wayne Mountjoy, G. T. Burrow, H. H. Lipp, and Joseph Haffty.

cobaltomenite, and the entire zone containing dolomite is coated with pascoite; this suggests relative enrichment of selenium and vanadium peripheral to ore.

ROCK ALTERATION

Altered rocks of several types are common in the Temple Mountain district. They are divided into two main groups: (1) altered rocks associated with ore deposits or collapse structures, and (2) altered rocks largely confined to certain stratigraphic units. The altered rocks in the first category can be subdivided according to association

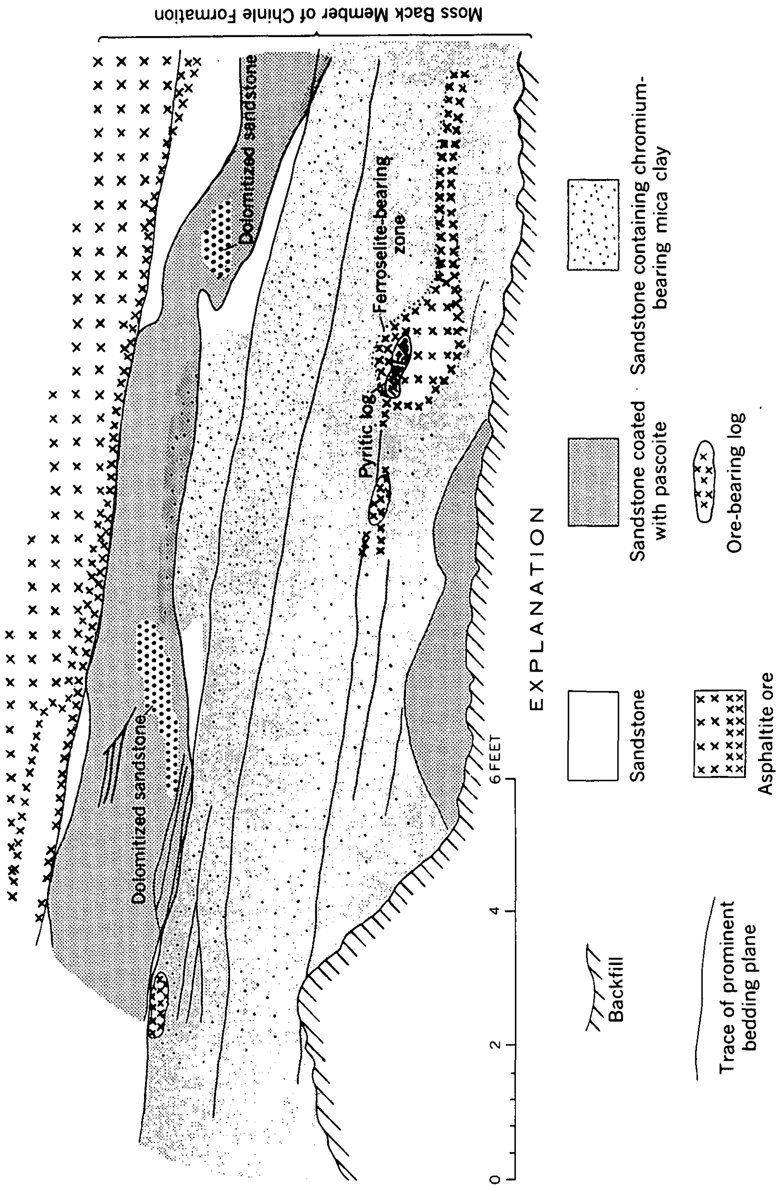


FIGURE 36.—Mineral zoning relations below a tabular ore body, Calyx 8 mine.

with both ore deposits and collapses or association with either one. Alterations common to both are the removal of carbonates and petroleum, dolomitization, and alteration and formation of clay minerals. Alterations specifically associated with ore deposits are chromian alteration and change in color and in composition of mudstone. An alteration specifically associated with the Temple Mountain collapse structure is the formation of siderite and possibly other iron-bearing minerals near the collapse. Altered rocks chiefly confined to certain stratigraphic units are found in the Moenkopi Formation, the Temple Mountain and Monitor Butte Members of the Chinle, and the Glen Canyon Group. In all three units altered rocks occur on a regional scale. The alterations of the Temple Mountain and Monitor Butte and Moenkopi Formation apparently are unrelated to the major uranium deposits and, therefore, have been described only briefly in the section "Stratigraphy." On the other hand, the alteration of the Glen Canyon Group seems to be related to the alteration associated with the collapse structures and is discussed briefly in this section.

ALTERATION ASSOCIATED WITH COLLAPSE STRUCTURES AND ORE DEPOSITS

Except in iron-rich areas, rocks in and near the collapses are lighter colored than unaltered rocks, and this bleached aspect is the most readily apparent result of alteration. The altered sandstones near ore are also typically bleached. Although the light color of the altered rocks is due in part to surficial removal of petroleum, it largely reflects the nonsurficial removal of iron minerals and petroleum and the formation of clay minerals during alteration.

REMOVAL OF CARBONATES

Carbonate minerals, chiefly calcite, were probably removed from the lower part of the Moenkopi Formation, certain zones in the Moss Back Member of the Chinle Formation, and more locally from other rock units. As noted previously (p. 42), the removal of carbonates from the lower part of the Moenkopi Formation was probably at least a contributory cause of the collapse structures.

The removal of carbonates from parts of the Moss Back is suggested by the sparsity of calcite in ores and adjacent altered rocks compared with its abundance in equivalent altered and unaltered rocks. It is also suggested by the sparsity of calcium indicated by the concentration ratios (table 7). The ores in the Calyx shaft mines commonly contain less than 0.5 percent $CaCO_3$. Southward from those mines, along the mineral belt, the carbonate content increases to 2 percent at the North Mesa 5 mine, reaches 2.6 percent in the Camp Bird 12 group, and is at a maximum of 7.15 percent in the Black Beauty mine, at the south end of the Temple Mountain mineral belt. Tests with dilute acid confirm the paucity of calcite in ore and altered rocks of the Calyx Bench and show its abundance in nearby stratigraphically equivalent rocks. It is inferred, therefore, that calcite was leached from sites that probably were mineralized slightly later. Farther from the collapse, in the south part of the mineral belt, either less calcite was leached or calcium carbonate leached from the sites of ore deposits near the collapse structure was reprecipitated.

REMOVAL OF PETROLEUM

The partial removal of petroleum from rocks in and near the collapse structures is shown by bleaching of altered unweathered petroliferous rocks. The petroleum was removed from fractures, bedding planes, and irregular areas (fig. 37) in these rocks, but only certain fractions were completely removed. This selective removal is attested to by the minute blebs of interstitial asphalt and rarely of acicular asphaltite(?) that are scattered through the bleached parts of the rock.

The altered rocks associated with ore are also nonpetroliferous. They do, however, contain blebs of interstitial asphalt; and because nearby stratigraphically equivalent unaltered rocks contain petroleum, the altered rocks are assumed to have been petroliferous prior to alteration. The nonpetroliferous, altered rocks are separated from the unaltered, petroliferous rocks by zones of asphaltite ore, as shown in the plan of the Calyx 8 mine (fig. 38). The removal of petroleum by the alteration process is also reflected by variations in the organic-carbon content of the petroliferous rock, ore, and nonpetroliferous rock across ore body 5 (fig. 34). The petroliferous sandstone contains about 1.8 percent organic carbon, whereas low-grade ore contains 3.9 percent, and high-grade, 11.6 percent. The altered rock immediately adjacent to ore contains 2.5 percent carbon, and altered rock 3 feet from ore contains virtually none.

It can be argued that petroleum was introduced after alteration and selectively entered the host rocks. The petroliferous rock is typically well cemented, however, and has a low porosity; in contrast, the nonpetroliferous, altered rock containing the interstitial asphalt is friable and porous. A widespread postalteration introduction of petroleum would, therefore, probably have led to saturation of the altered, now nonpetroliferous rocks. Furthermore, in some places crosscutting relations can be logically interpreted as indicating removal of petroleum before alteration associated with ore. For example, at the Vagabond mine petroleum was apparently removed from the vicinity of bedding planes in the Wingate Sandstone and a gray and white banded rock

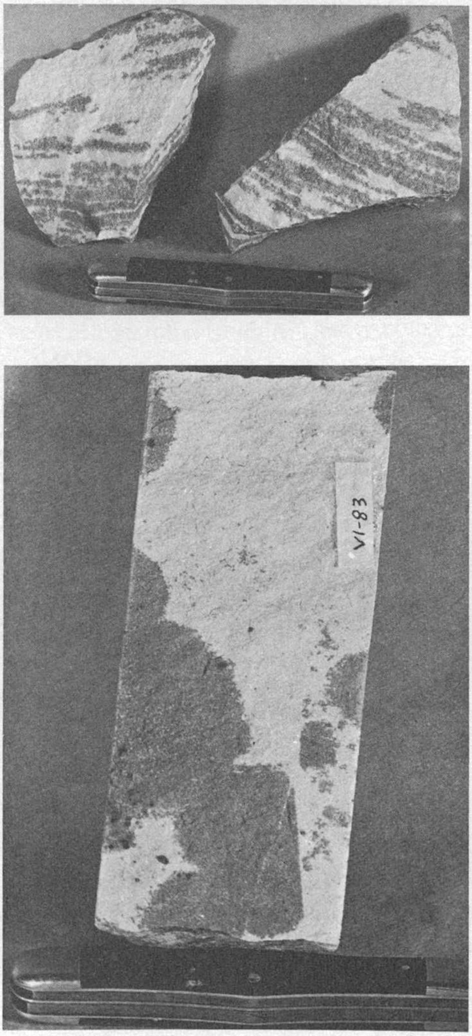


FIGURE 37.—Altered petroliferous sandstone from the Wingate Sandstone, South Temple Mountain (upper photo.), and from the Chinle Formation, Flopover, Temple Mountain (lower photo.).

was thereby produced, of which the gray bands are petroliferous and the white bands contain only scattered blebs of interstitial asphalt. A zone of asphaltite ore and associated chromium-bearing mica clay cuts sharply across the banded rock and is inferred to be younger than the banding (fig. 39). Relations in brecciated rocks of the collapse structures indicating early introduction of petroleum have been cited (p. 51).

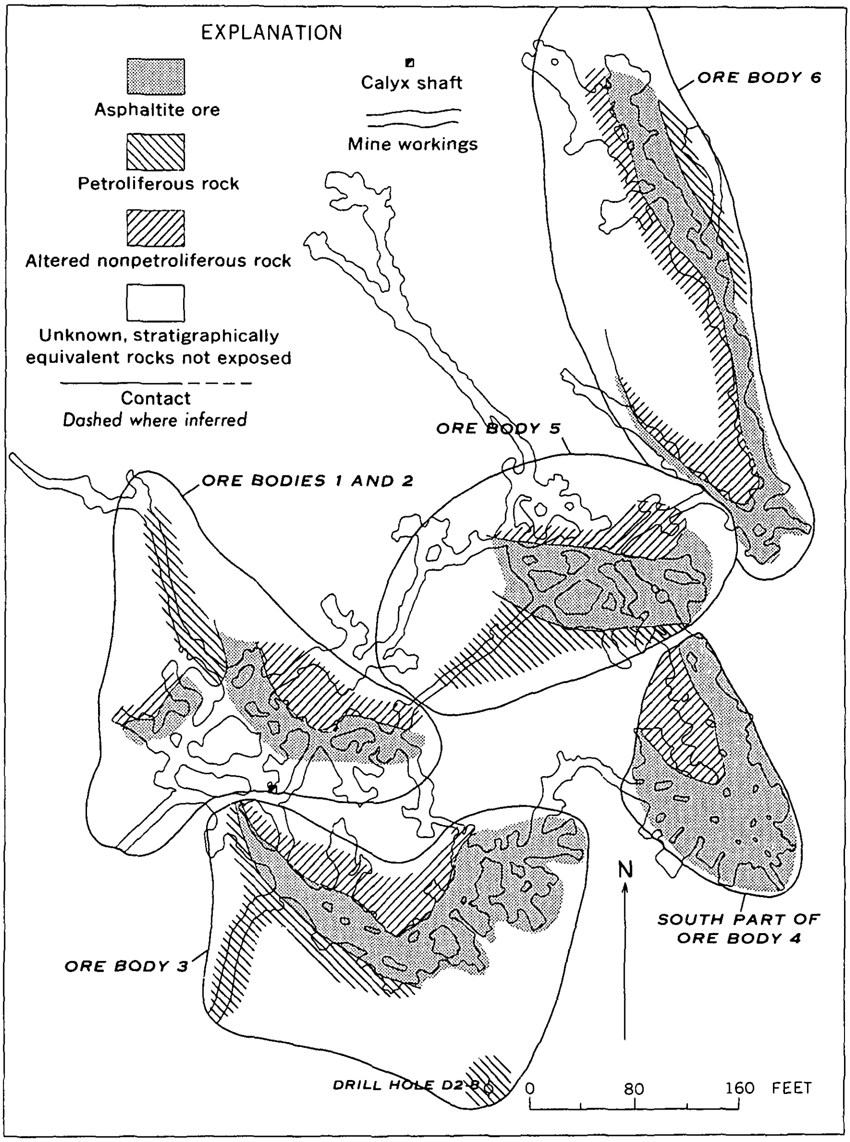


FIGURE 38.—Approximate distribution of asphaltite ore, petroliferous rocks, and altered, nonpetroliferous rocks, part of Calyx 8 mine. Mapped ore and rock are about at waist height and are about stratigraphically equivalent.

FORMATION OF CLAY MINERALS

Both kaolinite and mica clays appear to be more abundant in and near the Temple Mountain collapse than farther from the collapse. Near the collapse the clay minerals also are coarser grained, and the replacement of detrital grains by clay minerals is more pronounced. The clay minerals, visible megascopically as white interstitial spots, are not confined to weathered rocks but also occur in unweathered rocks in mines or drill cores.

In the gray-white banded rocks near the Vagabond mine (p. 111), the mica clays are more abundant in the white, nonpetroliferous parts than they are in the gray, petroliferous parts, and microscopic veinlets of clays are common along grain boundaries in bleached parts but are rare in the petroliferous parts.

Modal analyses of sandstones of the Moss Back suggest that the clay-mineral content of the altered Moss Back near the Temple Mountain collapse is about twice that of unaltered sandstones farther from the collapse. The modes of barren apparently unaltered sandstones of the Moss Back (table 2) suggest that the total clay content of these rocks is generally less than 20 percent; in contrast a specimen (TM-371) of typical bleached sandstone of the Moss Back from the Vanadium King 5 mine near the East collapse contained about 41 percent clay minerals, as can been seen in the following table:

Modal analysis (volume percent), sample TM-371

Quartz, feldspar, and detrital mica	56
Kaolinite (coarsely crystalline, replaces detrital grains)	22
Fine-grained mica clays (also late sericitelike clays)	19
Fine-grained rock fragments	1
Translucent asphaltite	2
Total	100

Kelley and Kerr (1957) previously noted the increased abundance of kaolinite and illite (probably the same as our mica clays) near collapse structures and ore. They also found a difference in the structure of the illite near ore, on which they reported as follows (op. cit., p. 1111): "the illite associated with the alteration and mineralization in the Moss Back at Temple Mountain consists of mixtures of one- and two-layer polymorphs. Increased abundance of the more ordered two-layer structure toward ore is suggested at the Camp Bird mines bordering the collapse."

DOLOMITIZATION AND FORMATION OF CHROMIUM-BEARING MICA CLAYS

Dolomite and chromium-bearing mica clays have formed in the rocks near the Temple Mountain collapse structure and in rocks near ore deposits. The largest dolomitized areas, as much as several hundred feet across, are in the upper part of the Church Rock Member of the Chinle Formation and in the Wingate Sandstone on Temple Mountain. The dolomite is clearly epigenetic: it is found in parts of the section that normally have only small amounts of carbonate minerals, it replaces detrital grains as well as cements, and it occurs in zones that cut across the sedimentary structures. Locally it contains disseminated copper sulfides. Weathered surfaces of dolomitic rock in which pyritelike minerals are disseminated locally are coated with cobaltomenite or malachite and azurite.

The uranium deposits in the Wingate Sandstone typically overlie dolomitized rocks and are overlain by chromium-bearing rocks. At the Vagabond mines the shape of the ore roll is about like that of the underlying dolomitized mass, and it is also reflected in a zone of chromium-bearing rocks that occurs above and on the sides of the roll ore body (fig. 39). According to spectrographic analyses (fig. 39), the chromium content of the altered sandstone is about 0.3 percent.

Both dolomite and chromium-bearing mica clays also occur near the ore deposits in the Moss Back, but the dolomitic and chromium-bearing zones are smaller and the spatial relation of altered zones to ore is different than in the Wingate Sandstone. The dolomitized zones in the Moss Back are 3 feet or less across and near most roll ore bodies are at the same level as the ore; they are closer to ore than are the bulk of chromium-bearing mica clays. In some tabular ore bodies, ore overlies the dolomitic and chromium-bearing rocks (fig. 36).

Dolomite is not found near ore bodies in the broken rocks of the collapse structures, but chromium-bearing mica clays are associated with ores exposed at the surface and those cut at depth in drill cores. Near the southwest corner of the Flopover, nearly vertical pipes and rolls of asphaltite ore are separated from the bleached rocks making up most of the collapse by a zone about 5 feet across impregnated with chromium-bearing mica clays.

The chromium-bearing and dolomitic rocks near the ore bodies are nonpetroliferous; they do contain interstitial asphalt, and dolomitized areas in the Moss Back Member contain the acicular asphaltite(?) shown in figure 22.

The formation of the dolomite and chromium-bearing mica clays probably took place about the same time as the formation of ore deposits. Some of the same elements are enriched in the dolomitic and chromian zones as are enriched in the ore deposits, and, although the change in uranium content at contacts between ore and altered rocks is abrupt, the changes in some other extrinsic elements are gradational and suggest a transition of ore and altered rocks by way of metal zoning.

The zones that have a low concentration of calcite coincide with zones containing chromium-bearing mica clays or dolomite, and removal or displacement of calcite probably took place in the same cycle of alteration as the formation of dolomite and chromium-bearing mica clays. An additional likelihood is that the composition of the solutions causing alteration changed with time and that calcite was dissolved somewhat before the formation of dolomite.

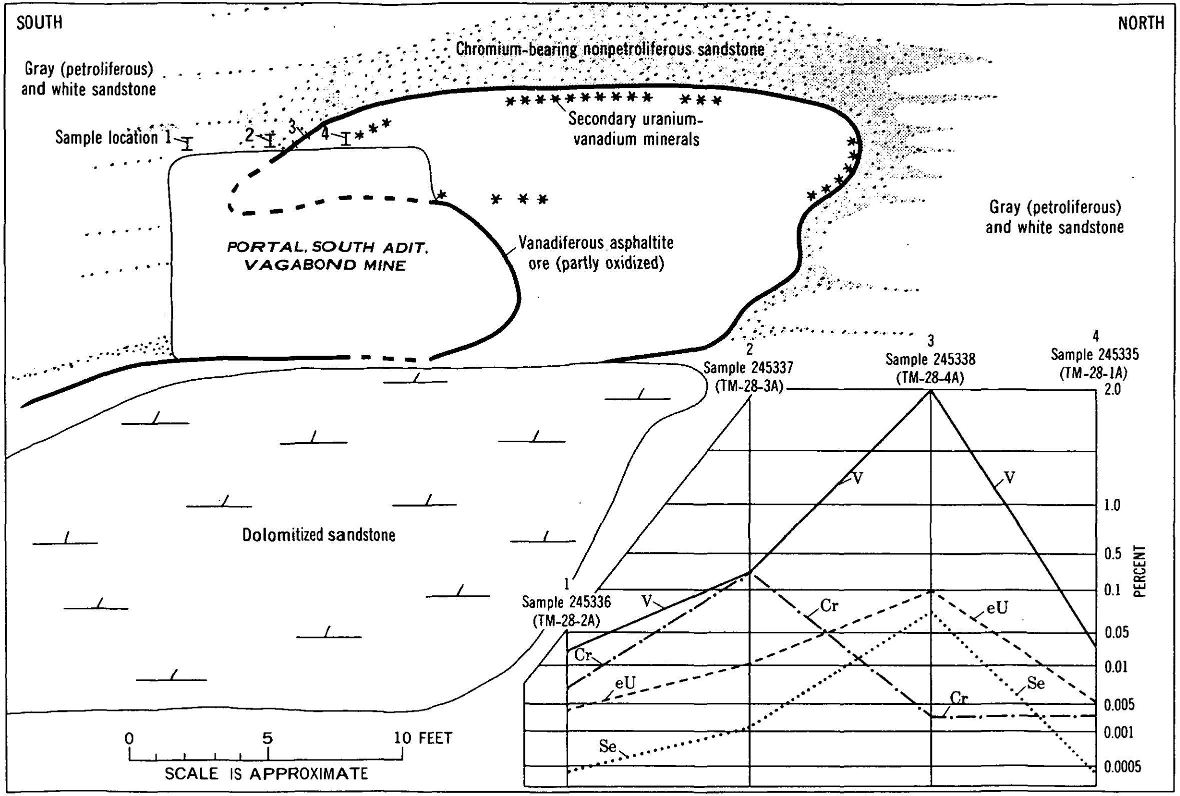


FIGURE 39.—Relation of altered rocks to ore in the Wingate Sandstone at the Vagabond mine. Vanadiferous asphaltite ore is dashed where mined out. Geology by J. G. Moore and C. C. Hawley, 1956; analyses by C. G. Angelo, H. H. Lipp, J. S. Wahlberg, and R. G. Havens.

CHANGES IN COLOR AND COMPOSITION OF MUDSTONE

The color and chemical composition of mudstones in the Moss Back Member near ore has been changed as a result of alteration. The mudstones in ore or in contact with ore are dark gray; the mudstones farther from ore are light green. The contact separating green from gray mudstone is a knife edge and locally cuts across the bedding. Chemically (table 14), the gray mudstone differs from the green mudstone by its greater concentrations of uranium, zinc, and probably copper. Chromium is more abundant in the green mudstone, and some elements, including barium, cobalt, nickel, and vanadium, are present in about the same concentrations in both green and gray mudstone.

The gray and green mudstones contain about the same concentrations of iron, calcium, and sodium as do barren mudstones from the Moss Back and Shinarump Members of the Chinle Formation, but apparently they contain more potassium, magnesium, and typical extrinsic elements than do the so-called barren mudstones.

TABLE 14.—*Chemical composition, in percent, of altered mudstones, Calyx 8 mine, and mudstones of the lower part of the Chinle Formation, Colorado Plateau*

	Semiquantitative spectrographic analyses of mudstones from Temple Mountain district, Calyx 8 mine				Average of barren mudstones of Colorado Plateau [1]
	Gray		Green		
Field No.	AEC-8-22A	AEC-8-32A	AEC-8-22B	AEC-8-32B	
Lab. No.	253146	288453	253147	288454	
U	0.3	0.15	0	0	0.0009
Si	>10	>10	>10	>10	>10
Al	>10	>10	>10	>10	9
Fe	1.5	1.5	1.5	1.5	1.6
Mg	1.5	1.5	1.5	3	.7
Ca	.3	.15	.3	.15	.17
Na	.3	.3	.3	.3	.5
K	7	7	7	7	.3
Ba	.07	.07	.07	.07	.017
Co	.003	.003	.003	.007	.0009
Cr	.015	.015	.15	.15	.006
Cu	.007	.015	.003	.003	.003
Ni	.015	.007	.015	.015	.0019
Pb	.015	.003	.007	.007	.0011
V	.3	.15	.3	.3	.012
Zn	.03	.03	0	0	≈.005

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[1] Partial estimated geometric mean composition of 18 samples from the Shinarump and Moss Back Members of the Chinle Formation (Newman, 1957, table 31, p. 484).

FORMATION OF SIDERITE NEAR THE TEMPLE MOUNTAIN COLLAPSE STRUCTURE

Siderite-rich masses containing minor amounts of possibly primary hematite and limonite are found near the contact of the Temple Mountain collapse and the downwarped adjacent sedimentary rocks (map of collapse area, pl. 1). Most of the siderite is in the Church Rock

Member of the Chinle, but some extends up into the Wingate Sandstone and also into the collapsed rocks. The mode of occurrence of the siderite resembles that of the dolomite, but siderite is mainly in the Church Rock, rather than in the Wingate, and is closer to the collapse.

The spatial relations of the siderite to bleached rocks in the Church Rock Member suggest that the siderite and bleaching are related. The zone of bleaching around the collapse flares upward from near the base of the Church Rock, and the zone of bleaching in the Church Rock is most extensive directly below the Wingate contact. The amount of ferruginous material varies directly with the thickness of the bleached zone (as the zone of bleached material thins away from the collapse, the ferruginous zone also thins and disappears). The zone of bleaching is only mappable on Temple Mountain, but a thin part of the upper part of the Chinle is bleached below the Wingate throughout much of the district. The correlation of the thickness of bleaching with iron concentrations suggests that iron was removed from the bleached zone and was redeposited nearby thus forming the siderite-rich masses.

ALTERATION IN THE GLEN CANYON GROUP

The rocks of the Glen Canyon Group are altered over much of the San Rafael Swell. In most places alteration products are confined to the structurally higher rocks of the group, but in the Temple Mountain district the alteration is pervasive. The altered rocks are bleached and locally contain small dolomite masses and bright-green (chromiferous?) mica clays. Bleached areas in petroliferous parts of the altered Glen Canyon Group rocks are similar to those found at Temple Mountain (fig. 37) and are inferred to indicate removal of some oil during alteration. In areas outside the district, the contact between altered and unaltered rocks is approximately level; this indicates that the alteration occurred after the folding of the San Rafael anticline.

The similarity of the regional alteration to alteration at Temple Mountain, which is seen in dolomitization, formation of mica clays, local removal of petroleum, and bleaching, suggests that the regional alteration of the Glen Canyon Group and the alteration at Temple Mountain are related. If they are related, the alteration at Temple Mountain is probably either the same age as or younger than the San Rafael anticline, as indicated by the relation of the regional alteration to that structure.

ORIGIN OF THE URANIUM DEPOSITS

Geologists have studied the uranium deposits in the Temple Mountain district at various times since 1913, and several hypotheses of origin have been proposed. Notable contributors of data and ideas have been, in approximate chronologic order, Hess, Murphy, Webber, Stokes, Gott and Erickson, Keys and White, Kerr and colleagues, Hausen, and Breger and Deul. Syngenetic and epigenetic hypotheses have been proposed, and according to various hypotheses, metals have been derived from sea water, petroleum, hydrothermal solutions, or from the rocks by lateral secretion. The hypothesis proposed in this report is that the uranium deposits formed epigenetically from uraniferous aqueous solutions introduced into the Moss Back Member and other strata through collapse structures. The introduced solutions reacted with petroleum contained in the rocks to form ore bodies dominantly composed of uraniferous asphaltite. This hypothesis is discussed in detail in pages 122–133. Some of the other hypotheses are in old reports or in unpublished reports; therefore, representative earlier hypotheses are summarized in the next section.

EARLIER HYPOTHESES OF ORIGIN

Hess (1922; 1933, p. 456–459) suggested that an asphaltic material absorbed metal from dilute solutions in a shallow sea and was transformed by the absorption process into asphaltite, which was subsequently deposited with what was called Shinarump and now is recognized as the Moss Back Member, a younger part of the Chinle Formation. Several other geologists, notably W. L. Stokes, R. C. Robeck (written commun., 1956), and H. S. Johnson, Jr. (1957), proposed an epigenetic lateral-secretion origin for the deposits. Stokes considered the thick massive sandstone unit at Temple Mountain to be part of a major paleochannel and he stated (written commun., 1946) that:

> the Temple Mountain channel was a strong well-marked aquifer for a very long period of time between the time of its burial under the Chinle and the time when the San Rafael Swell and surrounding territory was deformed so that underground circulation was disrupted * * *. During this time it is probable that vast quantities of ground water, some of connate origin and some from surface sources, were conducted through the channel. Small quantities of uranium and vanadium present in the water were precipitated by the carbonaceous or organic material (asphalt) and over a long period of time the present ore minerals were built up.

Hess (1922; 1933, p. 456–459) proposed that, after uplift of the San Rafael Swell, solutions from hot springs localized at the Temple Mountain collapse leached uranium and other metals from the syngenetic deposits and redeposited them in the Wingate Sandstone. Leaching by solutions from hot springs has also been accepted by Stokes and others, who advocate lateral secretion, to explain uranium deposits in strata other than the Moss Back.

In both the syngenetic and lateral-secretion hypotheses, asphalt is presumed to have absorbed metals from aqueous solutions and to have been transformed into asphaltite. An alternative possibility is that the asphaltite was derived from a metalliferous petroleum. G. B. Gott, R. L. Erickson, D. G. Wyant, and other geologists of the U.S. Geological Survey in the early 1950's recognized a general similarity between trace elements contained in crude oils and the trace elements contained in uranium deposits on the Colorado Plateau. Gott and Erickson (1952, p. 7) proposed that "uranium and other metals were transported in solution by migrating petroleum from more distant uranium deposits including the petroleum source bed." Wyant (written commun., 1953) proposed that, if the granular asphalt found interstitially in friable parts of the Moss Back were not of detrital origin, as proposed by Hess, a uraniferous crude oil may have been introduced into the district after folding of the San Rafael anticline, and asphaltite may have formed residually through loss of volatiles from the oil because of oxidation or polymerization; he further proposed that during late hydrothermal activity, parts of the asphaltite and petroleum, and the metals they contained, may have been leached and redeposited along fractures, and part of the asphaltite may have been mobilized and injected into veinlike masses along bedding.

As an alternate hypothesis, Gott and Erickson (1952, p. 7) suggested that the metal content of the asphaltite ores might be due to reaction with an older uranium deposit. They stated that "The uranium was present in the Shinarump conglomerate before the hydrocarbons migrated into it. When the hydrocarbons did come in contact with the uranium minerals, the uranium was transferred into the hydrocarbon fluids. The hydrocarbons most closely associated with the uranium were then polymerized by alpha particles * * *." This hypothesis, nearly the same as that generally given for the formation of thucholites (see Davidson and Bowie, 1951, for example), has been applied also to the Temple Mountain district by Hausen (1956; 1959) and by Isachsen and Evensen (1956, p. 273). Hausen also proposed that the ores in the collapses and in the bedded deposits are directly related in origin because of similarities in mineralogy, mode of occurrence of uraninite, alteration, and in relations between liquid and solid bituminous materials. The primary minerals (sulfides and uraninite) were considered by Hausen to be hydrothermal, mainly by analogy with the mineral assemblages found in some hydrothermal uranium deposits.

An hypothesis of hydrothermal origin was first advocated by B. N. Webber (written commun., 1944), who reported as follows:

> The Temple Mountain ore deposit is of hypogene hydrothermal origin * * *.
>
> The widespread alteration of sedimentary rocks in the vicinity of the Temple Mountain ore bodies; the number and nature of introduced elements and the subtraction of some elements from the altered rocks and the addition of others; as well as the tendency for the ore to follow faults and other solution channels and cut across a variety of formations of diverse nature, are considered ample evidence for a hypogene origin.
>
> The solutions affecting the Temple Mountain mineralization were of epithermal type * * *.
>
> The epithermal ore-bearing solutions moved upward and outward along whatever conduits were available, spreading from the main conduits, mainly faults, into coarsely clastic sediments such as the Shinarump conglomerate [now recognized as Moss Back Member at Temple Mountain] of upper Triassic age and the Wingate sandstone * * *.
>
> The fault pattern and alteration zone at the north end of Temple Mountain probably mark the principal locus of the ore-bearing solutions. The north Temple alteration zone is marked and partially bounded by a fault pattern roughly elliptical in plan enclosing a subsided block strongly suggestive of the "mineralization stoping pipe" type of deposit.

According to Webber, the asphaltite was deposited late in the paragenetic sequence.

Kerr and colleagues, including Keys, White, Kelley, Bodine, and Lapham, have generally advocated a hydrothermal origin in several papers that have been previously cited in the text. The evidence cited for hydrothermal origin in a general summary (Kerr and others, 1957, p. 977–980) included alteration—particularly dolomitization, formation of chromium-bearing mica clays, and changes in structures in the illites near the collapses—and the mineralogy of the deposits, especially the occurrence of uraninite, native arsenic, and some of the sulfides. Present-day hot springs in the north part of the San Rafael Swell, igneous dikes in the southwest part of the Swell, and the location of the collapses in a belt of faulting were also believed to point to hydrothermal activity. Metals added during mineralization and alteration were proposed to have been derived in part from the sedimentary rocks and in part probably from magmatic sources.

In nearly all the hypotheses, the asphaltite has been considered to be a petroleum derivative, but this was questioned by Breger and Deul (1959) and indirectly by Gruner (1956a). Breger and Deul (p. 149) concluded that:

> The carbonaceous material associated with the sandstone ore that we have studied is apparently derived from plant material that has been coalified, or from the low-rank coals of the region. It is possible that uranium- and vanadium-bearing solutions extracted organic matter from degraded plant debris in the sediments and that the mixture of carbonaceous material, uranium, and vanadium was subsequently deposited in porous sandstones. The present insolubility of the carbonaceous matter may be the result of cross-linkage of coal molecules caused by irradiation by the alpha particles from the uranium and its daughter products.

ESTABLISHED FACTS AND PROBABILITIES

Much new evidence has accumulated during the latest period of intensive study of the district, which began in 1944 with the work of the Union Mines Development Corp. Near-surface uranium deposits in the district are now known to be largely confined to the Temple Mountain and Flat Top areas. Points of general agreement are that the petroleum was introduced after sedimentation and that the asphalt and asphaltite are diagenetic or younger. The uranium deposits of the Temple Mountain district have been found to be at least qualitatively different from other uranium deposits in the San Rafael Swell. The deposits at Temple Mountain are highly seleniferous, and they contain relatively more vanadium and chromium and less copper and zinc than do the other deposits. They occur at higher levels in the Chinle Formation, and many ore bodies are in the form of rolls rather than tabular deposits. The deposits at Temple Mountain also differ from deposits elsewhere in the Swell by being closely associated with collapse structures and altered rocks.

Other features or relations of the deposits at Temple Mountain are less certain but appear probable from the available evidence. Several things suggest that the collapse structures and uranium deposits at Temple Mountain formed concurrently with or after the folding of the San Rafael anticline. The collapse structures of the San Rafael Swell are found in or near subsidiary folds of the main anticline and probably formed late in the folding. The parallelism of the Temple Mountain mineral belt and the monoclinal flexure that forms the east flank of the San Rafael Swell suggests that the ore deposits formed during or after folding. The alteration of the Glen Canyon Group, which almost certainly occurred at the time of or after folding, is similar to that associated with ore deposits and collapse structures. The ore deposits formed before most normal faulting. Folding most probably occurred in early Tertiary time, and, according to Spieker (1954, p. 13), normal faulting started at about the time of folding; therefore, the uranium deposits at Temple Mountain probably formed in early Tertiary time at about the time of folding but before most normal faults had formed.

PROPOSED HYPOTHESIS

The sequence of events that led to the formation of the major part of the ore deposits began during a period of structural activity with the accumulation of carbon dioxide-rich aqueous solutions in the upper part of the Coconino Sandstone. These solutions dissolved carbonate rocks and some siliceous rocks, leaving voids into which the overlying rocks collapsed. The solutions then migrated out into the rocks surrounding the collapses, altered them, and locally formed uranium deposits.

The chemical nature of the solutions changed with time from acid to alkaline by reactions with the country rocks and their contained fluids. At first, when acid, the solutions dissolved carbonate rocks and cements and formed kaolinite; later, when less acid or perhaps alkaline, they deposited dolomite, siderite, and the metallic ore minerals, and they added chromium and vanadium to disseminated clay minerals and to mudstones. The solutions also displaced part of the petroleum contained in the rocks and left small amounts of asphalt in place. The displaced parts were redeposited as uraniferous asphaltite at interfaces between the introduced carbon dioxide-rich aqueous solutions and petroleum-rich fluids contained in the rocks. The interfaces tended to be spherical; this accounts for the shape of the common roll ore bodies.

The source of some extrinsic elements, such as selenium, uranium, and arsenic, was probably at some distance from the deposits. The source of other extrinsic elements, such as chromium, vanadium, and nickel, may have been, in part, the heavy-mineral components of the rocks near the deposits. Calcium and magnesium may have been derived from the Sinbad Limestone Member of the Moenkopi and from the Kaibab Limestone, but they could also have come from more distant sources. The iron found in siderite near the Temple Mountain collapse probably had a local source.

The ultimate origin of the introduced fluids is a speculative problem, and we do not completely agree on its answer. Considerable parts of the introduced solutions either were derived from igneous rocks at depth or were formed by the mixing of connate waters and carbon dioxide-rich gases in a time of tectonic and possibly igneous activity.

ORIGIN AND CONTROLS OF ASPHALTITE-RICH ORES

The derivation of the asphaltite at Temple Mountain has been the subject of considerable controversy. The consensus of opinion, represented by Gott and Erickson (1952), Keys and White (1956), Kerr and others (1957), and Hausen (1956, 1959), is that the asphaltite was derived from petroleum. In 1959, however, Breger and Deul presented evidence suggesting that the asphaltite was derived from coaly materials. Some coaly materials are known to be partly soluble in aqueous, especially alkaline aqueous, solutions; so coal extracts could have formed the asphaltite. The idea that coaly materials significantly contributed to the formation of asphaltite at Temple Mountain, however, is unacceptable for several reasons, the first and most significant of which is the field relations. The asphaltite ore occurs adjacent to altered rocks, which were probably petroliferous prior to the mineralization; away from the altered rocks the asphaltite grades imperceptibly into petroleum in unaltered rocks. These relations are explained by the hypothesis proposed but not by that offered by Breger and Deul.

Breger and Deul (1959, p. 140, 149) emphasized that coaly materials are abundant in ore-bearing units on the Colorado Plateau but that petroleum is generally sparse, except at Temple Mountain, where it is associated with coaly material and with ore. It seems more reasonable to emphasize the abundance of petroleum at Temple Mountain. The Chinle Formation contains scattered coaly materials, but the main ore-bearing unit, the massive sandstone unit of the Moss Back Member, contains only minute amounts of coaly material, and minor ore-bearing units, the Coconino and Wingate Sandstones, contain none. The mineralized units are, however, petroliferous at Temple Mountain.

Some of the chemical evidence supporting a coaly origin was presented on pages 92–94, where we noted that chemical considerations do not point conclusively to either coal or oil as a parent material for the asphaltite. We also stated that certain of the anomalous physical and chemical properties of the asphaltite are doubtless due to radiation since precipitation of asphaltite.

Coal extracts may be locally incorporated in the asphaltite, but they are in no way essential. We have concluded that the ore deposits would have about their present shapes, sizes, and compositions if oil alone had been present in the rocks at the time of mineralization. If, however, coaly materials alone had been present, the ore deposits would very likely differ greatly in size, shape, and organic content and would closely resemble other ore deposits in the Chinle Formation, such as those of the Delta mine, which are composed mostly of uraninite and sulfides but do contain scattered carbonaceous ore masses of obviously coaly origin.

The asphaltite seems to be chiefly a product of a reaction between an introduced carbonated aqueous solution and petroleum contained in the rocks. It formed largely from petroleum fractions displaced by the introduced solutions. The petroleum incorporated in the asphaltite was derived from the zones of altered rocks that occur adjacent to ore and are not now petroliferous but do contain small amounts of interstitial asphalt. The displacement mechanism is suggested mainly by the paucity of petroliferous material in the altered rocks; it is, however, also mechanically feasible. Water is used in secondary recovery to displace oils, and carbonated water is known to be a more effective recovery agent than ordinary water (Johnson and others, 1952). Carbonated water or liquid carbon dioxide causes a decrease in viscosity and interfacial tension of the petroleum and this leads to increased extraction.

The distance of displacement of oil fractions was variable. Apparently the oil fractions incorporated into asphaltite in high-grade parts of ore bodies near sharp ore contacts were moved as much as several tens of feet. The asphaltite in lower grade ores, near gradational contacts with petroliferous rocks, apparently formed almost in place.

The lithology of the massive sandstone unit, channel deposits of the unit, the monoclinal warp along the southeast edge of the mineral belt, and the collapse structures were larger scale features that determined the places of deposition of the asphaltite. Small-scale sedimentary structures and physical-chemical factors determined the detailed shapes of the ore bodies. The physical-chemical factors include surface-tension phenomena and chemical reactions.

The detailed shape of ore bodies is inferred to have been largely controlled by physical phenomena. In particular, the typical roll shape of Moss Back ore bodies is inferred to be that assumed by the surface of an aqueous solution introduced into lenticular sandstones saturated with a petroleum-rich fluid—principally petroleum but with small amounts of trapped water and dissolved gases, such as H_2S. The shape assumed by the introduced solution would have a minimum surface area because of the interfacial tension between the introduced solution and petroleum; it would therefore tend to be spherical, or bubble shaped. Variations in shapes of roll ore bodies were probably caused by local permeability barriers; generally tabular ore bodies are inferred to have formed adjacent to more nearly planar masses of introduced solutions.

The differences in the location of altered zones relative to the deposits in the Moss Back Member, the Wingate Sandstone, and the Temple Mountain collapse structure may be explained by the relative confinement of altering and mineralizing solutions. In the Moss Back deposits the altered, leached rocks are on the inner, concave sides of rolls; this indicates that the altering solutions were confined and channeled by parts of the host sandstone lenses. In contrast, the alteration in the Wingate deposits (as at the Vagabond mine) is on the outer, convex sides of the rolls; this suggests that the introduced aqueous fluids were mainly outside the present ore bodies and that the ores formed at an interface surrounding a remnant of petroleum-rich fluid. In the collapse structures the ores are confined to the outer parts of downfaulted masses. This is explainable in at least two ways. An obvious possibility is that the faults forming the boundaries of the collapses served as channelways for ore-bearing solutions, and so ore bodies might be expected near the faults. A second possibility is suggested by distribution of ore and altered rocks in the deposits in the Moss Back Member. Paired C-roll ore bodies of the Moss Back can be pictured as forming around a core of altering and mineralizing solutions that occupied the altered zone that is in contact with the ore. Perhaps the ore bodies of the collapses formed around similar but larger bodies of altering solutions that virtually saturated the collapse. Both mechanisms may have contributed, but the second is considered more probable because the faults themselves are not appreciably mineralized. Ore in the southwest part of the Flopover has the associated chromian alteration on the side of the ore toward the center of the collapse, and this apparently strengthens the analogy with ore deposits in the Moss Back, where paired roll deposits apparently formed around a core of introduced fluid.

The influence of interface phenomena on the shapes of some ore bodies in the Morrison Formation and in other Jurassic rocks was recognized and discussed by Shawe (1956). According to Shawe's interpretation (1956, p. 241) interfaces that controlled ore shapes in Jurassic rocks apparently formed between two aqueous solutions of different chemical and physical properties, rather than between an aqueous solution and a petroleum-rich fluid. Shawe considered the position of the interfaces to be relatively constant, and he implied that the ore minerals were precipitated at the interface over a relatively long period of time. In the deposits of the Moss Back Member at Temple Mountain, however, the leached nature of altered sandstone indicates that the interface was not a static one. The mineralizing solutions displaced oil from the zones now composed of altered rocks; as more solution was added the interface between oil and water was pushed back and the altered zone was enlarged. Rapid deposition of uraniferous asphaltite at the interface is perhaps borne out by the rare occurrence of Liesegang banding of asphaltite at ore contacts (p. 86); this type of banding results, most likely, from supersaturation phenomena and indicates rapid precipitation once a certain limit of supersaturation has been reached (McBain, 1950, p. 206, 207). Some of the petroleum now contained in the Moss Back at Temple Mountain contains several hundred parts per million uranium; therefore, much larger concentrations of uranium seemingly would possibly be stable for a short period of time and petroliferous solutions supersaturated with respect to uranium seemingly could have been present during the period of ore formation.

The cause of precipitation of the asphaltite from the transported oil fractions is speculative. Hausen (1959) and others proposed that petroleum migrated into a uranium deposit composed largely of uraninite, montroseite, and sulfides and that alpha radiation caused polymerization and consequent solidification of petroleum to form the asphaltite. During polymerization some of the uranium and other metals in metallic minerals were dissolved. Although this mechanism is in agreement with microscopic paragenetic studies and the metalliferous nature of the asphaltite, it conflicts with megascopic paragenetic data. Petroleum was probably in the rocks prior to uranium mineralization, and further, the constant association of uraninite and asphaltite suggests that both were derived from the same solution and are largely contemporaneous. Since polymerization must be gradual, some other factor might have caused the precipitation of uraninite and asphaltite at about the same time. A factor that seems to be consistent with the observed alteration and with mineral and asphaltite precipitation is an increase in pH. Such an increase, due to the reaction of the introduced carbonated solutions with detrital quartz and feldspars and with carbonate cements, is suggested chiefly by the concentrations of dolomite near ore. Increased pH near the site of ore deposition might also be inferred from the formation of asphaltite. Carbon dioxide increases the mobility of petroleum in secondary recovery; therefore, loss of free CO_2 from a carbonated solution (hence a higher pH) probably would favor the precipitation of oil components, contained in the oil-water mixture, as asphaltite.

Although the effectiveness of alpha radiation as a precipitating mechanism for the asphaltite may be questioned, radiation has almost certainly been important in causing the hydrogen deficiency of asphaltite, its insolubility, and possibly, its anomalous hydroxyl and oxygen content (p. 94).

Kerr and Kelley (1956), Kelley and Kerr (1958), and Abdel-Gawad and Kerr (1961) proposed that the asphaltite was formed by the mingling of introduced hydrothermal solutions and petroleum contained in the Moss Back Member and adjacent strata, and that the asphaltite was converted to its present state by heat supplied by the hydrothermal solutions. Abdel-Gawad and Kerr (1961, p. 405–407) showed that fluid asphalt from the Temple Mountain district can be significantly altered by heating to about 250°–300° C; the infrared absorption pattern of the heated asphalt resembles that of asphaltites from the Temple Mountain district and the Tomisch Mountain mining area of the San Rafael Swell. It is extremely unlikely, however, that such temperatures existed in the environment in which the asphaltite formed. Regardless of whether part of the solutions have some igneous affiliation, it seems certain that the igneous source is deeply buried and that any components supplied by such a source to the site of mineralization would have only a small effect on the temperature dictated by the geothermal gradient.

The zonal distribution of elements observed on a large scale in the Temple Mountain area and on a small scale near many ore bodies is a major problem of the district. If, as we believe, nearly isothermal conditions prevailed in the district, then concentrations of metals and complexing agents such as CO_2 or H_2S in the ore fluid seem the most likely cause of zoning. Regardless of its cause, the large-scale zonal distribution of uranium, vanadium, and selenium in the Temple Mountain area is probably the chief evidence pointing toward the Temple Mountain collapse area as the location of the conduit for the solutions causing mineralization.

The small-scale zoning at ore boundaries in the Temple Mountain district is almost duplicated in many uranium-vanadium ore bodies of the Colorado Plateau, particularly those in the Entrada Formation and in the Salt Wash Member of the Morrison Formation. E. M. Shoemaker (written commun., 1956) proposed that the similar zoning of minor elements at the boundaries of the vanadium deposit near Rifle, Colo., was caused either by differential absorption or differential diffusion. Shawe (1956, p. 241) suggested that the "different response of various elements or ions to temperature and concentration differences across the interfaces would account for the asymmetric layering of minor elements in ore bodies."

NATURE OF THE INTRODUCED SOLUTIONS

The introduced solutions that caused alteration and mineralization were aqueous. When introduced they were rich in free carbon dioxide and, consequently, were slightly acidic; they are inferred to have been reducing solutions but to have had a low sulfide-ion content. Carbon dioxide was present mainly in bicarbonates, subordinately in solution, and possibly in a separate phase (Garrels and Richter, 1955). The acidity and free carbon dioxide content of the solutions decreased with time because of reactions with carbonates and other minerals. The more general alterations, such as removal of calcite, displacement of petroleum, and formation and recrystallization of kaolinite, occurred while the solutions were slightly acidic. The formation of dolomite and siderite, changes in composition of mudstone, and ore deposition occurred when solutions were slightly alkaline.

The effects of the general alteration are compatible with a slightly acidic (pH 5–7) solution rich in free carbon dioxide. The solution need not have been very acidic to dissolve calcite and to form kaolinite.[8]

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[8] Kaolinite, although locally formed under very acidic conditions (Lovering, 1950, p. 240, 243–247), can also form under nearly neutral conditions if alkali and alkaline earth elements are removed about as fast as they are liberated from altered rocks (Grim, 1953, p. 329). This would probably be true if soluble carbonates or bicarbonates were formed.

The deposition of dolomite and siderite near the ores is compatible with an alkaline solution rich in carbonate ions. The formation of some illite or sericitelike clays in and near ore is probably also more compatible with alkaline solutions. Hemley (1959) showed that at constant temperature, the stability fields of kaolinite, mica, and potassium feldspar are traversed, in this order, with increasing K^+/H^+ ratio. The change from kaolinite to mica corresponds to either a decrease of H^+, an increase in K^+, or to some combination of both factors. In general the formation of micas with respect to formation of kaolinite can be considered as favored by increasing pH.

The sulfide-poor but somewhat reducing nature of the altering solutions is inferred mainly from the state of occurrence of the iron near the collapses. Most of the iron is in siderite rather than in pyrite (which could indicate more reducing, sulfide-rich solutions) or hematite (which might indicate deposition from more oxidizing solutions). The solutions, especially those introduced into the Moss Back Member, probably became more reducing because of reactions with solutions containing hydrogen sulfide derived from either the petroleum or coal.

The postulated carbon dioxide content of the mineralizing solutions is also in keeping with the transport of uranium. Laboratory studies of uranium solubility have demonstrated the existence of soluble uranium carbonate complexes; soluble uranyl carbonate complexes were found by Gruner (1956b. p. 497–502), and a uranous carbonate complex was reported by McClaine, Bullwinkel, and Huggins (1956, p. 30). Most of the recent studies on uranium transport have emphasized the uranyl carbonate complexes and precipitation of uranium as uraninite by reduction. Hostetler and Garrels (1962) showed that uranium and vanadium can be transported together in mildly reducing conditions, with uranium as a uranyl carbonate complex, and that uraninite and montroseite will be deposited with reduction or acidification of the solutions. P. B. Hostetler (oral commun., 1961) also questioned the stability of the reduced uranium complex in dilute natural solutions.

Several things, however, suggest to us that transport of uranium in the +4 (reduced) state must be evaluated more extensively before it can be eliminated from consideration. Significant solubility of uranium in carbonate solutions after reduction by H_2S at temperatures of 100°–200° C was reported by Rafalsky (1958, fig. 11). Furthermore, the deduced sequence of alteration and mineralization in the district does not seem to fit the model for uranium deposition proposed by Hostetler and Garrels. Although mineralizing solutions were introduced into a reducing environment of strata containing petroleum and H_2S, the precipitation of uranium probably was not immediate but took place only after considerable movement and reaction of solutions with the host rocks. Furthermore, the change in pH that took place in reaction was not one of increasing acidity, but rather one of increasing alkalinity of the solutions. If uranium can form both oxidized and reduced soluble complexes then some of the conflicting relations are resolved. For example, uranium present as a uranyl carbonate complex might not be precipitated upon entering a reducing environment but might go to a uranous complex, which could be precipitated later by changes in acidity. In this connection, it may be noted that the uranous complex found by McClaine, Bullwinkel, and Huggins (1956, p. 30) would hydrolyze with increasing alkalinity, and the uranous hydroxide thus formed would dehydrate to theoretical uraninite, UO_2.

SOURCES OF EXTRINSIC ELEMENTS AND SOLUTIONS

The metals contained in the introduced solutions could, theoretically, have been derived from several sources; certainly there is no compelling reason for them all to have been derived from only one source. The available evidence suggests derivation from several sources at different distances from the present deposits.

Possible sources of metals in the host rocks of the ore include volcanic ash and its alteration products and some of the detrital heavy minerals that are now present in trace amounts. Heavy minerals are probably the more likely source. The Moss Back Member itself is not known to be rich in volcanic materials, and although the Temple Mountain and Monitor Butte Members of the Chinle do contain volcanic ash, the ash was highly altered previous to alteration related to the collapse structures. The earlier alteration shows no recognizable relation to the major introduction of ore elements in the district. In general, although rocks rich in volcanic ash are widespread on the plateau, there is little evidence to show a genetic relation of the ash to the ore deposits (McKelvey and others, 1955, p. 501). On the other hand, work in the Slick Rock district of Colorado led Shawe and colleagues to conclude that chromium, vanadium, nickel, copper, and some other elements could be derived in part from common detrital minerals, because they had found these elements in the opaque heavy minerals, such as hematite, magnetite, and ilmenite, that occur in unaltered rocks. In equivalent altered rocks these heavy minerals are not as abundant (Shawe and others, 1957, p. 52–53) and so evidently were partly destroyed during alteration. The altered rocks also have been found to contain, on an average, smaller amounts of chromium and vanadium than do the unaltered rocks (D. R. Shawe, oral commun., 1959); this suggests leaching of these metals during alteration. Similar heavy minerals are present in the rocks of the Temple Mountain district. In view of the extensive alteration, it seems likely that at least part of the vanadium and chromium and perhaps some other extrinsic elements were derived from the destruction of heavy minerals during alteration.

If the petroleum migration hypothesis is correct some of the metallic elements found in the deposits were introduced by the oils, because the oils themselves are everywhere metalliferous. Chemical evidence suggests, however, that the asphaltite was not derived by the residual concentration of metal-rich fractions of the oils. A residual-concentration origin was suggested by the similarity of the trace-element suites found in the oil and in the ore (Gott and Erickson, 1952; Erickson and others, 1954); but even though the suites are similar, the oil contains some elements (such as tin) that are not present in the asphaltite, and concentration ratios deduced from relative amounts of metals present in oil and asphaltite differ widely. If the petroleum were residually concentrated, concentration ratios would be about the same for all elements. To get the amount of uranium now present in the asphaltite by concentration of metalliferous petroleum would require concentration ratios ranging from over 100 for the most uraniferous oil extract to over 20,000 for the least uraniferous extract, which is, itself, more uraniferous than any of 29 crude oils studied by Erickson, Myers, and Horr (1954, table 1). Apparent concentration ratios for some of the other metals range from zero for zinc in some oils to over 100 and are generally erratic for zinc, cobalt, chromium, and vanadium.

In contrast to the elements probably present in relatively soluble heavy detrital minerals, such elements as selenium, uranium, and arsenic are not known to be present in relatively available form in the nearby rocks. These elements are therefore proposed to have come from more distant sources. The case for a distant source of selenium is particularly strong (as shown by Coleman and Delevaux, 1957) because selenium is not abundant in the Chinle Formation and is only slightly enriched in other Chinle ore deposits (Shoemaker and others, 1959, p. 50). Little evidence is available on the source of certain other extrinsic elements, among which are copper, lead, and zinc. Lead, in galena, is most abundant in the deposits in the collapse structures, which may indicate introduction from a more distant source along with the selenium, uranium, and arsenic. Some of the zinc and probably trace amounts of lead, copper, and uranium were introduced into the rocks from an unknown source before the main period of ore formation. This earlier mineralization is marked by the early sphalerite in coals; it is tentatively correlated with the deposition of trace amounts of copper, zinc, and uranium minerals in the chert that was formed during the regional alteration of the Temple Mountain and Monitor Butte Members of the Chinle.

The more common elements, magnesium, calcium, and iron, that are enriched in or near the deposits may also have had several sources. The magnesium and calcium (largely in dolomite) may have been derived from nearby sources, such as the Kaibab Limestone and the Sinbad Limestone Member of the Moenkopi. More distant sources are also possible, however, because the Kaibab may not have been present under the Temple Mountain collapse structure, and magnesium may have been added to the Sinbad Limestone Member, which is completely dolomitic in the Temple Mountain district but only partly dolomitic in most other places in the San Rafael Swell. The iron in the ferruginous masses at Temple Mountain was probably derived from the adjacent rocks (p. 117).

The source of the carbon dioxide, inferred to have been a major component of ore-forming solutions, is speculative. Various origins for natural gases and waters rich in carbon dioxide have been proposed. Dobbin (1935, p. 1067–1069) gave as possibilities incipient metamorphism of basement rocks, oxidation of hydrocarbons by mineralized waters, and volcanism. The first two mechanisms would probably furnish small amounts of carbon dioxide through long periods of time, but volcanism with addition of large amounts of carbon dioxide and other contaminants would perhaps be a triggering step that would throw normally alkaline ground waters out of balance and initiate a cycle of alteration and ore formation. Gases rich in carbon dioxide are now contained in the Coconino Sandstone and Kaibab Limestone of the less deeply eroded Last Chance and Woodside anticlines, which, respectively, lie 35 miles southwest and 40 miles northeast of Temple Mountain and are subsidiaries of the San Rafael anticline (Gilluly, 1929, p. 129; Anderson and Hinson, 1951, p. 120, 121); natural gases rich in carbon dioxide probably were also present in the San Rafael anticline prior to deep erosion. The gases of the subsidiary anticlines also contain helium, and as helium in natural gases is generally considered to be of radiogenic origin (Rogers, 1921, p. 68; Gott and Hill, 1953, p. 118, 119), the presence of helium in the Permian rocks suggests concentrations of uranium minerals in the Permian and older rocks of the region.

Other indirect evidence suggests hydrothermal activity as a factor in the genesis of the deposits at Temple Mountain. The metal content of the Temple Mountain deposits is similar to that of some vein-type uranium deposits. Fischer (1959, p. 225–229) emphasized that vanadium is not enriched in most vein-type uranium deposits. It is, however, locally enriched in the Schwartzwalder deposit in Jefferson

County, Colo., and it occurs in possibly commercial amounts with uranium in the large vein-type uranium deposits of the Lake Athabaska area, Canada (Robinson, 1955, p. 68). As recognized by Robinson (1955, p. 101), the occurrence of vanadium and selenium with uranium at Lake Athabaska is similar to the association of these metals in deposits on the Colorado Plateau. Cobalt, nickel, copper, and some other metals are also enriched in both groups of deposits. It can also be inferred that the vein deposits of the Lake Athabaska area were deposited from carbon dioxide-rich relatively sulfur-poor solutions similar to solutions inferred at Temple Mountain. The sequence of alteration minerals—kaolinite, then mica clays and carbonates—at Temple Mountain is similar to that in many deposits of hydrothermal origin. Neither metal content nor alteration sequence, however, point directly to a magmatic source of hydrothermal solutions, although they probably indicate at least an indirect relation of igneous activity to the genesis of the uranium deposits at Temple Mountain.

SUGGESTIONS FOR PROSPECTING

The outlook for discovery of large tonnages of ore in the vicinities of Temple Mountain and Flat Top is not good.

The most likely place in the district for the discovery of additional ores is probably the Temple Mountain mineral belt, even though this area has been the most extensively mined and explored. Somewhat less likely places are the part of Temple Mountain that lies updip from the mineral belt, and the Temple Mountain collapse structure. Small ore bodies may be found on Flat Top and in other collapses. Vanadiferous uranium ores occur in the Wingate at several places but they are small and are difficult to reach.

Deposits may occur in the parts of the Chinle that underlie the thick sandstone beds of the Glen Canyon Group in the east part of the district. If, however, the known deposits are related to the collapse structures and are largely limited to the Flat Top and Temple Mountain areas, then any deposits that may be present downdip are probably not genetically related to the known ores and so are not necessarily controlled by the same features. Other collapses may be buried beneath the thick sandstone cover of the eastern San Rafael Swell, and these could have associated ore deposits. Crossfolds, ring-type faults, and alteration products would be guides to the location of buried collapse structures.

Several of the deposits in the Temple Mountain mineral belt have been extensively mined since 1956, but the belt still seems to have the best possibilities for future discovery of ore. In the early days of exploration the configuration of the ore bodies was not known, and some mine and drill-hole surveys were inaccurate. The ore bodies are generally elongate in a northwest direction, and in places two or more ore horizons are superposed and separated by barren intervals. To accurately delineate ores of this type, close horizontal and vertical control of drilling is needed. During parts of the earlier exploration, the drill holes were not accurately surveyed and the collar altitudes not determined, and so the depth to ore zones, except in relative distances, was not known. We infer, therefore, that even where drilling was sufficiently extensive to block out the general mineralized areas, unmined ores may be present nearby. These ores might be found by vertical or inclined long-hole drilling from mine workings. According to local miners such long-hole drilling revealed considerable amounts of ore in the Calyx 3 mine.

Additional ore bodies will probably be found in the Moss Back Member updip from the mineral belt. Individual ore bodies, or closely spaced groups, containing as much as 2,000 tons of ore are exposed at several places around the rim of North Temple Mountain, and small ore bodies probably are present inside the mountain. Fracture zones have guided mining in the Vanadium King 5 mine, and similar fracture zones near the collapse structure might be useful prospecting guides. South Temple Mountain appears less promising than North Temple Mountain. There are two small mines between the North Mesa 10 mine and the Flopover, and small ore bodies have been found in the inclines updip from the mineral belt, but so far exploration by drilling has been disappointing. Of about 35 holes drilled by the U.S. Atomic Energy Commission west and south of South Temple Mountain along the rim of Moss Back, only one penetrated ore (A. H. Anderson and R. D. Miller, written commun. 1952).

The Temple Mountain collapse structure contains small ore bodies near the west end of the Flopover, near the east side of the East collapse, and, probably, at depth near the Coconino-Moenkopi contact. It contains larger amounts of slightly uraniferous mineralized rock. Large-scale sampling by the Union Mines Development Corp. (F. M. Murphy, written commun., 1944) and core drilling by the U.S. Atomic Energy Commission (A. H. Anderson and R. D. Miller, written commun., 1952) have both indicated that the most uraniferous part of the collapse is near the west end of the Flopover.

Maps of roll trends in the deposits in the Moss Back Member probably would aid in prospecting as well as in mining. Some rolls in the Moss Back Member have a paired ore body at about the same stratigraphic position. The paired ore bodies are separated by altered rocks containing interstitial asphalt and, locally, green, chromium- bearing mica-clay and dolomite. It therefore seems reasonable to explore away from a known ore body, through noticeably altered rocks, for a paired ore body. Green, chromium-bearing mica clays and dolomite, in nonpetroliferous sandstone, occur within a few feet of ore and should be a general guide to ore.

Although no further specific guides for prospecting are known, there may be ore deposits in more deeply buried rocks. Small amounts of sulfides noted in the Sinbad Limestone Member of the Moenkopi and the occurrence of considerable galena at depth in the collapse structures suggest that more deeply buried carbonate rocks may contain base-metal sulfide deposits. The presence of helium in Permian rocks in the Woodside anticline and in other subsidiary features may indicate uranium deposits in the more deeply buried rocks.

MINES

Several of the mines in the area were mapped and studied, and these studies are the basis for most of the descriptive material in the general section "Uranium Deposits." Geologic maps were made of the Calyx 8 mine (the largest mine of the district), the North Mesa 1, 2, and 5 mines, part of the Camp Bird 12 group of mines, two small mines in the Wingate Sandstone, and the ore deposits that crop out on Flat Top. These mines and areas are described in this part of the report. The data obtained in reconnaissance examination of other mines have been noted, where applicable, in previous sections.

CALYX 8 MINE

The Calyx 8 mine, the most productive mine in the district, is on the Calyx Bench south of the Vanadium King 1 mine; it is the northernmost of the Calyx mines. The mine was opened in 1952 and by the end of 1956 had produced about 42,000 tons of ore that averaged about 0.27 percent U_3O_8 and 0.90 percent V_2O_5. The mine was operated during this time on lease by the Cline brothers of Green River, Utah.

The mine is operated mainly through a drilled calyx shaft 37 inches in diameter; it is also connected with the surface through the Calyx 11 mine and the Vanadium King 1 adit. (The connection with the Vanadium King 1 is in the far northeast part of Calyx 8; it was driven after our survey was completed.) The workings of the Calyx 8 mine are over 3,500 feet long and in general consist of northwest-trending stopes connected by northeast-trending haulageways in barren or poorly mineralized rock (pl. 4). Geology of the walls along some of the drifts is shown in a fence diagram (pl. 4).

The main workings are entirely in the Moss Back Member of the Chinle Formation, but the shaft is collared in the Church Rock Member. The contact between Moss Back and Church Rock Members in the shaft is at about 40 feet below the collar.

Most of the ore occurs in fine- to medium-grained massive to crossbedded sandstones of the massive sandstone facies of the Moss Back. Some ore occurs in conglomeratic sandstone and in fine-grained massive to very finely crossbedded sandstones. Some characteristics of the rock units in the mine may be seen in the fence diagram (pl. 4). The sandstones that are known to contain ore are in the lower half of the Moss Back and occur in a vertical range from slightly less than 5 feet to about 40 feet above the base of the Moss Back. Individual sandstone lenses are as much as 20 feet thick but average about 8 feet thick. The lenses are separated by conspicuous bedding planes or mudstone layers that are as much as 3 feet thick.

The general strike of the base of the Moss Back, as determined from widely spaced drill holes, is about N. 40° E., or somewhat more easterly than it is farther south on the Calyx Bench. The rocks are cut by a group of northwest-striking high-angle fractures that are particularly abundant in the northeast part of the mine and continue into the Vanadium King 1 mine. Most of the fractures are faults that have vertical or horizontal displacements of 2 feet or less. The faults displace the ore bodies and locally most contain lustrous somewhat viscous asphalt, which is not appreciably radioactive.

Asphaltite is commonly the only megascopically visible component of the ore. Pyrite and rarely galena and sphalerite are visible in both uraniferous and nonuraniferous coals. Ferroselite is present as minute crystals above a small ore body in the south part of Blanket Stope (fig. 36, pl. 4) and probably occurs near ore boundaries in other parts of the mine.

Secondary uranium and vanadium minerals are not abundant, but coatings of carnotite, corvusite, pascoite, and cobaltomenite are found on ore and on altered rocks near ore.

Silicified, coalified, and pyritized fossil wood is scattered through the mine; it is abundant only in mudstone and conglomerate-rich units. Of 28 fossil logs mapped (locations plotted on pl. 4) only 5 were noticeably radioactive and these contained asphaltite.

Several ore bodies have been developed to such an extent that their shape is known or can be inferred with reasonable confidence. These ore bodies are numbered 1–6 in an inset on plate 4 and are discussed below. Ore body 1 is a small but high-grade body exposed in the west part of the mine; it generally contains over 0.7 percent U_3O_8. The north contact of the ore is a roll, which trends generally northeast, but the overall shape of the ore body is approximately tabular. The ore is confined by two mudstone-rich beds to a sandstone unit as much as 4.5 feet thick. The ore pinches out to the south with the pinchout of the sandstone host rock.

Ore body 2 is exposed about 80 feet east of ore body 1; both ore bodies 1 and 2 probably belong to a complex group that has been mined near the Calyx shaft. The northeast contact of ore body 2 is a roll, which has been followed 120 feet northwest; the southwest contact is gradational and is approximately 40 feet southwest of the roll. Along the line of section (pl. 4) the roll is a C roll; it becomes more complex both to the north and south. An upper axis, shown by the dot-dash trace on plate 4, has been followed north in a short overhand stope. A complicated series of roll ore bodies lacking any recognizable trend is exposed along the north rib of the drift between ore bodies 1 and 2 and apparently marks the approximate northwest limit of the ore bodies exposed in stopes near the main shaft.

Ore body 3, shown diagrammatically in figure 10, is exposed in the Big Heading 50 feet south of the shaft. The ore body trends generally northwest and has been followed for 160 feet. The northeast contact of the ore is sharp and is a roll; ore extends southwest from the trace of the roll for 20 feet and grades into slightly mineralized petroliferous sandstone. At the short crosscut that extends south from the main shaft, the roll has the shape of a lazy W open to the east; the ore along the upper axis (dot-dash pattern) extends farther north and has been mined in an overhand stope. Southward, the shape of the roll changes greatly, and 110 feet south of the crosscut the ore body is tabular. Here the general trend of ore swings northeast, and the ore body ends to the south in a series of tabular lobelike bodies.

Ore body 4 is exposed in the Blanket Stope and in an upper drift that continues to the northwest. Probably the most productive ore body in the mine, it has been followed 360 feet; an unmined gap of 20 feet remains over the main haulageway. Near its north end the ore body was as much as 15 feet thick. As shown in figure 11, the ore body changes northward from a tabular body to a roll.

Ore bodies 3 and 4 are separated by only 40 feet of barren ground; their general relations suggest that they are largely mirror-image roll ore bodies that terminate to the south in a nearly continuous blanket ore body.

Ore body 5 is exposed along the main haulageway 310 feet northeast of the Calyx shaft cross sections are shown in figures 11 and 34 and on plate 4. The ore body trends about N. 85° W., is chiefly tabular, and has been followed for 120 feet. The northeast contact of the ore body is a roll; the ore extends about 50 feet to the southwest and grades into petroliferous sandstone. Along the haulageway the ore ranges from 4 to 6 feet in thickness and is confined to a crossbedded sandstone unit by mudstone-rich rocks. The mudstone-rich unit that caps the sandstone pinches out to the north and the ore thickens northward to as much as 8 feet. Northeast of the roll contact, along the haulageway, the sandstone unit is altered but not uraniferous, and the haulageway climbs above the unit. The same unit may, however, contain ore farther to the northeast, and a paired, mirror-image ore body is shown about 40 feet north of ore body 5. The inference is largely based on the distribution of the altered rock, but low-grade ore occurs in a small underhand stope, and ore has been intersected in a vertical drill hole near the inferred ore body.

Ore body 6, consisting of two mirror-image ore bodies, is exposed in the northeast part of the mine. Along a section (fig. 11 and pl. 4) through the haulageway the ore bodies are largely C rolls; they are in the same stratigraphic horizon and are separated by a zone of altered rocks. The rolls end to the south in a poorly defined tabular mass of ore. North from the section line the east roll has been followed directly 320 feet; the west roll has been followed 120 feet, but data from drilling indicate that it continues to the northwest. The north part of the ore body is only partly mined and its shape is uncertain; a short cross section through drill holes 4279 and 4300 (inset, pl. 4) shows the possible shape of the ore body.

NORTH MESA 1, 2, AND 5 MINES

The North Mesa 1, 2, and 5 mines (pl. 5) are accessible through adits in the southwest end of the Calyx Bench. Mines 2 and 5 are connected, and the same ore horizon was mined in parts of the 1 and 2 mines. All three mines are on the Camp Bird 13 claim.

Some ore was mined near the outcrop in all three mines before 1944, as shown by Union Mines Development Corp. maps (F. M. Murphy, written commun., 1944). According to Jess Abernathy (oral commun., 1957), a tabular body mined in the Blanket Stope between North Mesa 2 and 5 in 1948–52 was the most productive ore body.

The mine workings are in the Monitor Butte Member of the Chinle and in the quartzose conglomerate and massive sandstone facies of the Moss Back Member; all the ore, however, is in the Moss Back.

The rocks strike generally N. 30° E. and dip 12° SE. The mine area is just north of an east-striking fault on which about 80 feet of vertical displacement (south side down) has occurred, but this fault appears to have little effect on the general strike and dip of rocks near the mines. Subsidiary faults whose displacements are measured in inches are exposed near the portal of the North Mesa 1 mine, and a conspicuous north-striking fracture is exposed in the North Mesa 2 mine.

Three ore bodies are exposed in the three North Mesa mines. One is exposed near the portal of the North Mesa 5 and is mainly in the conglomeratic sandstone unit of the Moss Back Member. This ore body trends generally west-northwest and grades out southwest into petroliferous sandstone. A second, major ore body is the largely mined out tabular body in the Blanket Stope, between the North Mesa 5 and 2 mines. This ore body was nearly confined to a north-trending conglomeratic sandstone lens near the base of the Moss Back. The lens was 80 feet wide, 120 feet long, and as much as 12 feet thick. A cross section of the lens, as inferred from exposures in pillars, is shown in section *A–A′*, plate 5. The ore occurred in scattered nodules in the sandstone and in massive layers in the conglomerate near its contacts with other rocks. Some high-grade asphaltite ore, with galena and sphalerite, occurs in veins in silicified, coalified logs very near the base of the Moss Back. A third ore body crops out at the portals of the North Mesa 1 and 2 mines in the massive sandstone unit of the Moss Back Member (section *C–C′*, pl. 5). As the ore body is partly eroded, its trend is not known, but mineralized rock exposed near the portal of the North Mesa 2 mine grades westward into barren petroliferous rocks. The ore body in the Lopez incline (fig. 3), just south of the large high-angle fault mentioned above, may be a downfaulted continuation of this ore body.

CAMP BIRD 12 GROUP

The Camp Bird 12 group of mines, sometimes referred to as the South Workings, are in the Moss Back Member north of South Temple Wash. They are the southernmost large mines of the Temple Mountain area. Among the oldest mines in the district, they were extensively worked before 1944. The production before 1948 is not known, but it probably was at least several hundred tons of high-grade ore (over 1 percent U_3O_8). The mines were operated again from 1948 to 1952, but since that time the only mining has been in the ribs and pillars of the old workings. Part of the ore produced after 1948 was from the mine dumps of the earlier period of mining.

The mine workings consist chiefly of a series of interconnected open stopes, of which one group is along the main Moss Back outcrop belt, and another opens into a minor drainage to the east and is connected with the first group by the Through adit. The mine map (pl. 6), although not up to date, indicates the general outline of the workings. The sections show more than can be seen in the present exposures. In 1947, when the sections and outcrop sketches were made, exposures of both asphaltite and carnotite ore were extensive, but they have since been mined out.

The ore in the mines occurs in the massive sandstone facies of the Moss Back Member, and ore bodies crop out in and near altered friable sandstone zones that overlie or underlie a massive lens of petroliferous sandstone. The mines are in a downdropped segment of the Moss Back Member that is bounded on the north by a series of en echelon east-striking faults and on the south by the west-northwest striking fault in South Temple Wash (pl. 1).

Carnotite concentrations that have now been mined were peripheral to the black, unoxidized ores. Where asphaltite and carnotite were associated, most of the carnotite was in wavy layers 1–3 inches thick separated by nonuraniferous sandstone layers of equal thickness, all in a zone as much as 3 feet thick above or below the asphaltite-rich ore. The ores of this type appear to belong to the class of ore bodies called "diffusion rolls" (B. N. Webber, written commun., 1947). The uranium now present in carnotite is inferred to have moved as much as 3 feet from the site of the primary ore body. Other carnotite-bearing ores, such as the body mined in the Main adit (pl. 6), have the form of C rolls and probably formed largely in place by oxidation of the asphaltite ore.

The general relations of mine workings and the few remaining exposures of ore suggest that the Camp Bird 12 group of mines was on two mirror-image roll ore bodies that terminated to the south in a massive ore body. The east roll, exposed in the Through adit, trended north; the west roll, exposed along the outcrop, trended north-northwest.

CAMP BIRD 7 MINE

The Camp Bird 7 mine is in the Moss Back Member on the northwest corner of Temple Mountain. The main workings consist of two adits connected by a drift and a raise in the south adit. The north adit (fig. 40) contains most of the ore. The south adit trends east-northeast mainly in barren petroliferous rock and was not mapped.

Asphaltite and arsenic minerals are megascopically visible components of the ore. Native arsenic occurs as flattened nodules (probably formed by replacement of pebbles) in unoxidized ores and in rocks overlying ore; realgar and orpiment occur as coatings on the mine walls.

At least two and possibly three ore bodies are exposed in the mine (fig. 40). A tabular seam of asphaltite 3–6 inches thick has been mined in the back of the opencut near the portal. The seam thickens toward the portal and is as much as 1 foot thick in a small pillar left at the portal. The seam is approximately concordant to the bedding in the opencut but cuts across the bedding at an angle of about 6° near the portal.

An ore body in the northeast part of the mine is as much as 2½ feet thick and has been followed northeast for 80 feet. It has the form of a C roll, and curving Liesegang-like layers of asphaltite, as much as 1½ inches thick, outline the curving roll boundary. The tabular ore body

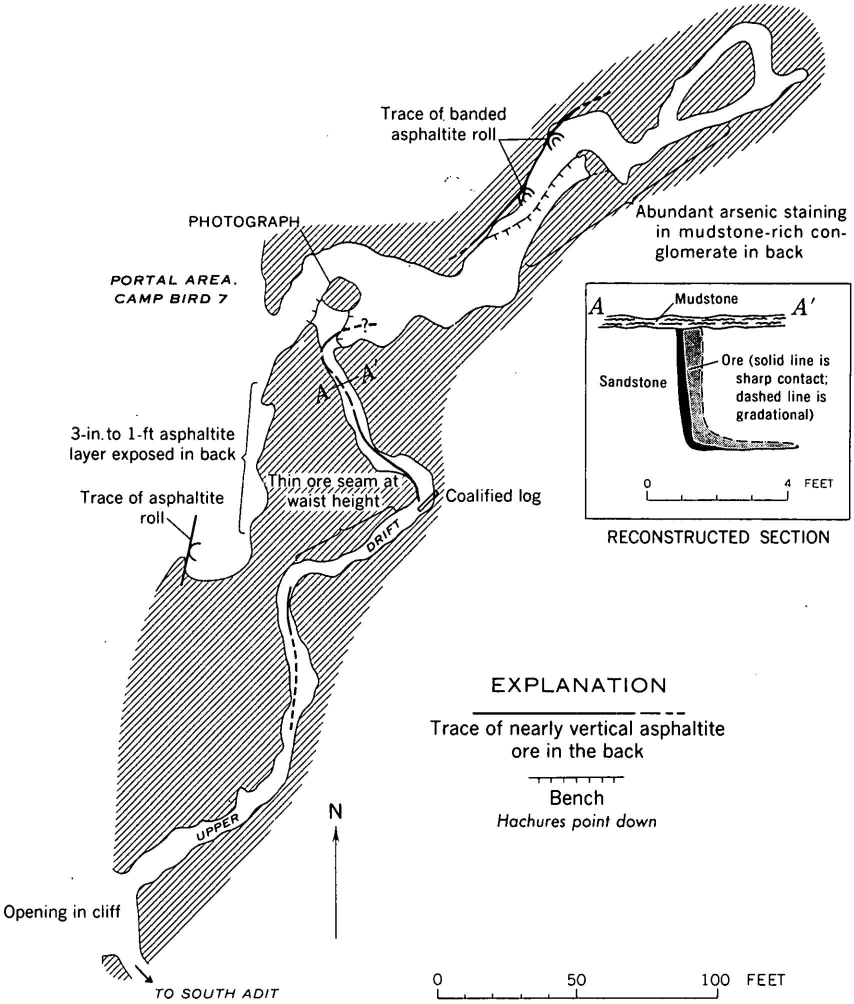

FIGURE 40.—Map of the Camp Bird 7 mine showing trends of roll ore bodies in the Moss Back Member (oblique-line pattern). Locality of figure 14 shown by "PHOTOGRAPH." Plan by P. H. Dobbs, R. L. White, and E. C. Winterhalder, U.S. Atomic Energy Commission, 1956.

exposed near the portal of the mine projects toward this ore body, and it seems likely that both actually are part of a single ore body.

The upper drift in the mine (fig. 40) followed a sinuous ore body or series of ore bodies. In the north part of the drift, the ore trends north-northwest for 60 feet. Ore is exposed near the back in a nearly vertical 8-inch zone and in the east rib in a thin nearly horizontal seam. The nearly vertical ore ends abruptly at a mudstone seam in the back. Exposures suggest that the general shape in cross section is that of an L (section A–A′, fig. 40). The ore trends southwest for 50 feet then turns to almost due south.

DEPOSITS EXPOSED ON FLAT TOP

Small amounts of ore have been produced from deposits on Flat Top, a small mesa in the west part of the Temple Mountain district. The mesa is capped by the Moss Back Member of the Chinle Formation, and all production has come from the Moss Back. Nineteen major occurrences of uranium minerals were observed in the cliffs forming the sides of the mesa during a detailed study of the mesa in 1947. Some of the occurrences were opened by short adits. Since that time, uranium deposits have been found by drilling in the interior of the mesa, and these deposits have been mined mainly from two opencuts. The largest deposits are in the north part of the mesa in the massive sandstone unit of the Moss Back Member (pl. 7).

According to records compiled by R. C. Robeck and H. B. Dyer, some ore, which averaged about 0.15 percent U_3O_8 and 0.67 percent V_2O_5, was produced on Flat Top between 1948 and 1951. From 1951 to 1956 there was little mining activity because the claims were under litigation. Mining was resumed in 1957, and at least several thousand tons of ore has been produced since then.

Occurrences of uranium minerals are found in the conglomeratic sandstone, massive sandstone, and limestone-pebble conglomerate units of the Moss Back Member. The uppermost unit, the platy sandstone, is eroded from near the edges of the mesa except near the south end of Flat Top. Occurrences of uranium minerals in the basal conglomeratic unit are exposed on the northwest and southeast parts of the mesa (sections *A–A′* and *B–B′*, pl. 7); other occurrences are in friable fine- to medium-grained sandstones in the limestone-pebble conglomerate unit along the west side of the mesa (section *A–A′*, pl. 7). None of the above-mentioned occurrences appear to be minable.

On the basis of studies in 1947, a northwest-trending ore zone in the massive sandstone unit was inferred to cross the north part of the mesa. This inference has generally been borne out by drilling and, since 1957, by mining. According to the miners, however, the ore bodies are smaller and less continuous than had been inferred from drilling. The largest exposed deposits are within 400 feet of the north pinchout of the massive sandstone unit on the north part of the mesa (sections *A–A′* and *B–B′*, pl. 7). They are in zones of friable sandstone containing interstitial asphalt and consist of small tabular and roll ore bodies containing asphaltite, coalified wood, and carnotite.

VAGABOND MINE

The Vagabond mine is in the Wingate Sandstone and in the Church Rock Member of the Chinle Formation on the east side of South Temple Mountain. The workings consist of two short adits in the Wingate Sandstone and an opencut in the Church Rock Member (fig. 41).

A small amount of mineralized rock rich in vanadium has been shipped. A mill-pulp sample representative of about 37 tons assayed 0.08 percent U_3O_8 and 0.86 percent V_2O_5.

The Wingate Sandstone and the Church Rock Member are conspicuously altered near the mine. Chorium-bearing mica clays impregnate a zone several feet wide above and laterally away from the mineralized zone in the Wingate Sandstone. Dolomite impregnates sandstone below the ore body exposed in the south adit and also below the mineralized zone exposed in the opencut.

Most of the ore is partly oxidized and contains carnotite, metahewettite, and, probably, metazeunerite in addition to asphaltite. Metahewettite occurs in veinlets as much as one-eighth inch across in the Wingate; the metazeunerite(?) forms thin coatings on asphaltite in the Church Rock Member.

Ore and mineralized rock occur in rolls and in tabular zones. The main deposit is a roll. The south part of the roll is exposed in the south adit and has been followed for about 40 feet. The ore zone is 6 inches thick or less and encloses petroliferous sandstone; it, in turn, is bordered by chromiferous or dolomitic sandstone (fig. 39). A second ore body in the form of a tabular seam along a bedding plane is exposed in the north adit. An asphaltite-bearing roll has been followed for about 40 feet in the opencut in the Church Rock Member; in most places the asphaltite-bearing zone is only about 3 inches thick.

MIGLIACCIO PROSPECT

The Migliaccio prospect is opened by two short adits in the upper part of the Wingate Sandstone on North Temple Mountain (fig. 41). It is accessible by a steep trail which crosses the north end of the saddle between North and South Temple Mountains. The history of the prospect is not known, but some ore was probably brought down by pack mule during the early mining in the district.

The ore is largely oxidized and consists of brown, purplish-gray, and yellow minerals, which probably include rauvite and possibly uvanite. The ore zone averages about 6 inches in thickness but is locally as much as 2 feet thick. The east adit appears to follow a northwest-trending roll that grades into a tabular ore zone near the face. The same tabular zone is also exposed in the west adit and extends to the west in outcrop. Chromium-bearing mica clays impregnate the sandstone above ore, and the ore roll in the east adit is above a small lens-shaped dolomite mass, which apparently trends north. If projected along this apparent trend, the dolomite mass would crop out on the north side of North Temple Mountain in the extensive dolomite-bearing zone below the Eagles Nest mine. This may indicate

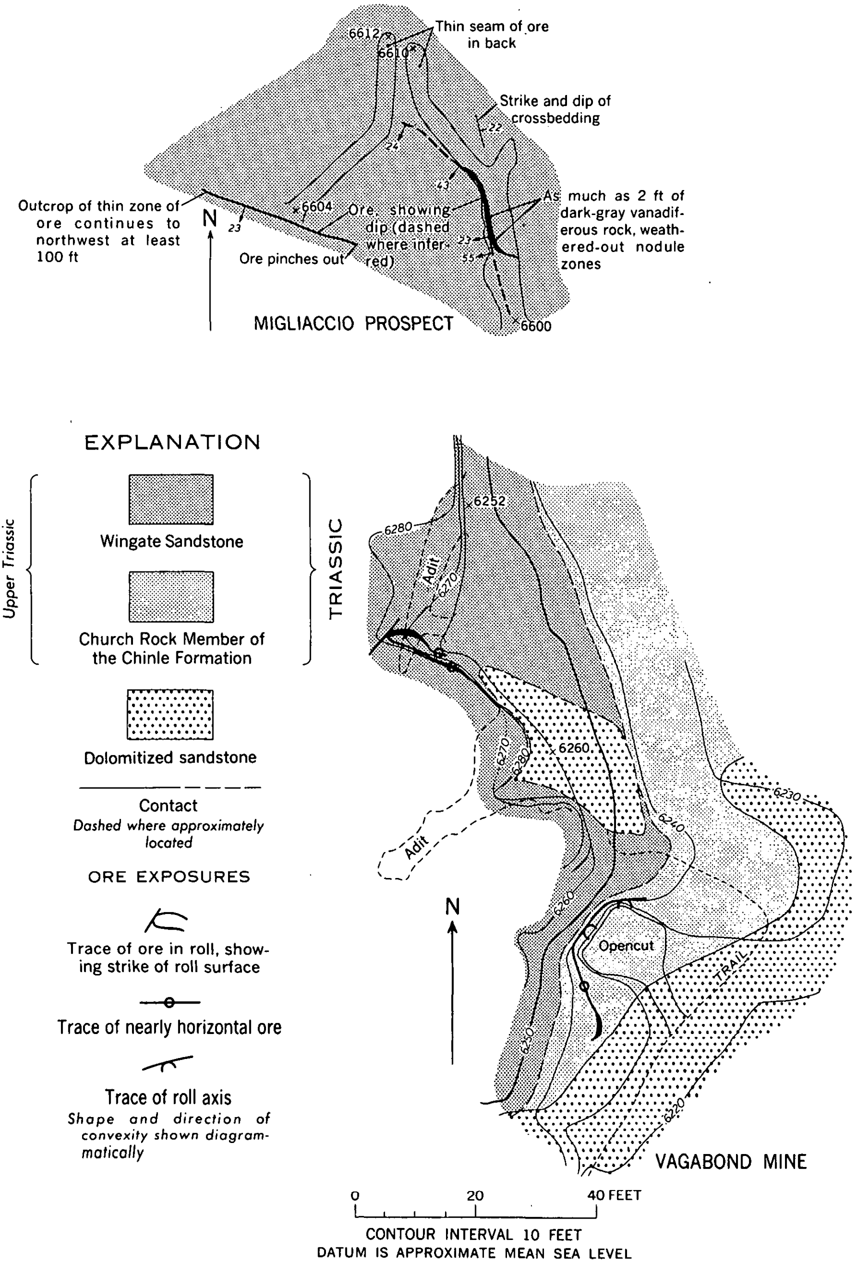

FIGURE 41.—The Vagabond mine and Migliaccio prospect.

that both the Migliaccio prospect and the Eagles Nest mine are on a generally north-trending ore zone that extends through North Temple Mountain above the dolomitized zone.

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INDEX

[Italic page numbers indicate major references]

U. S. GOVERNMENT PRINTING OFFICE : 1965 O - 772-655