GEOLOGY OF THE VIRGIN AND BEAVERDAM MOUNTAINS, ARIZONA

by
Richard T. Moore
Principal Geologist

THE ARIZONA BUREAU OF MINES

Bulletin 186
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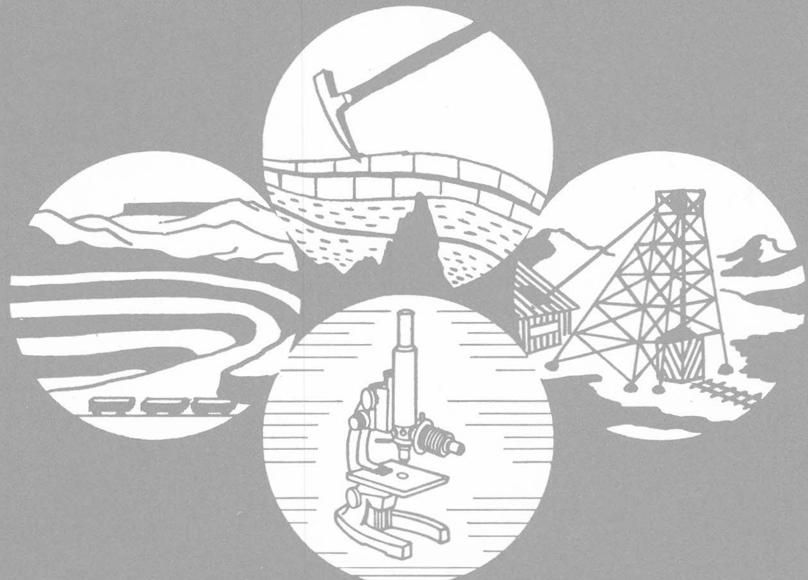

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ABSTRACT

The Virgin and Beaverdam Mountains form an arcuate range in northwestern Mohave County, Arizona, which extends northeasterly from the Nevada State line and swings to a northerly trend near the Utah boundary. The range lies on the eastern edge of the Basin-and-Range province, adjacent to the Plateau province, and has a maximum topographic relief of nearly 6,500 feet.

Rocks ranging in age from Precambrian to Tertiary are exposed in the Virgin and Beaverdam Mountains. Precambrian rocks consist of a metamorphic and igneous complex. The Paleozoic Era is represented by marine carbonate rocks with subordinate, fine-grained clastic material. Mesozoic and Cenozoic rocks are for the most part clastic units of continental origin.

Structural elements that have played a major part in the development of the range include a large anticlinal fold and a zone of reverse faulting that extends for nearly 20 miles along the eastern flank of the range. The basic pattern established by these structures has been modified by high-angle faults of large displacement which strike substantially parallel with the line of reverse faulting, and by transverse faults of less displacement. In the northern part of the range low-angle thrust faulting is locally prominent.

The structural elements can be divided temporally into three episodes of deformation: (1) post Jurassic to mid-Cretaceous(?) folding and thrust-faulting along north-trending axes, (2) late Cretaceous to pre-Middle Miocene folding and steep reverse faulting along northeast trending axes, and (3) Late Pliocene(?) to Recent normal faulting striking northeasterly.

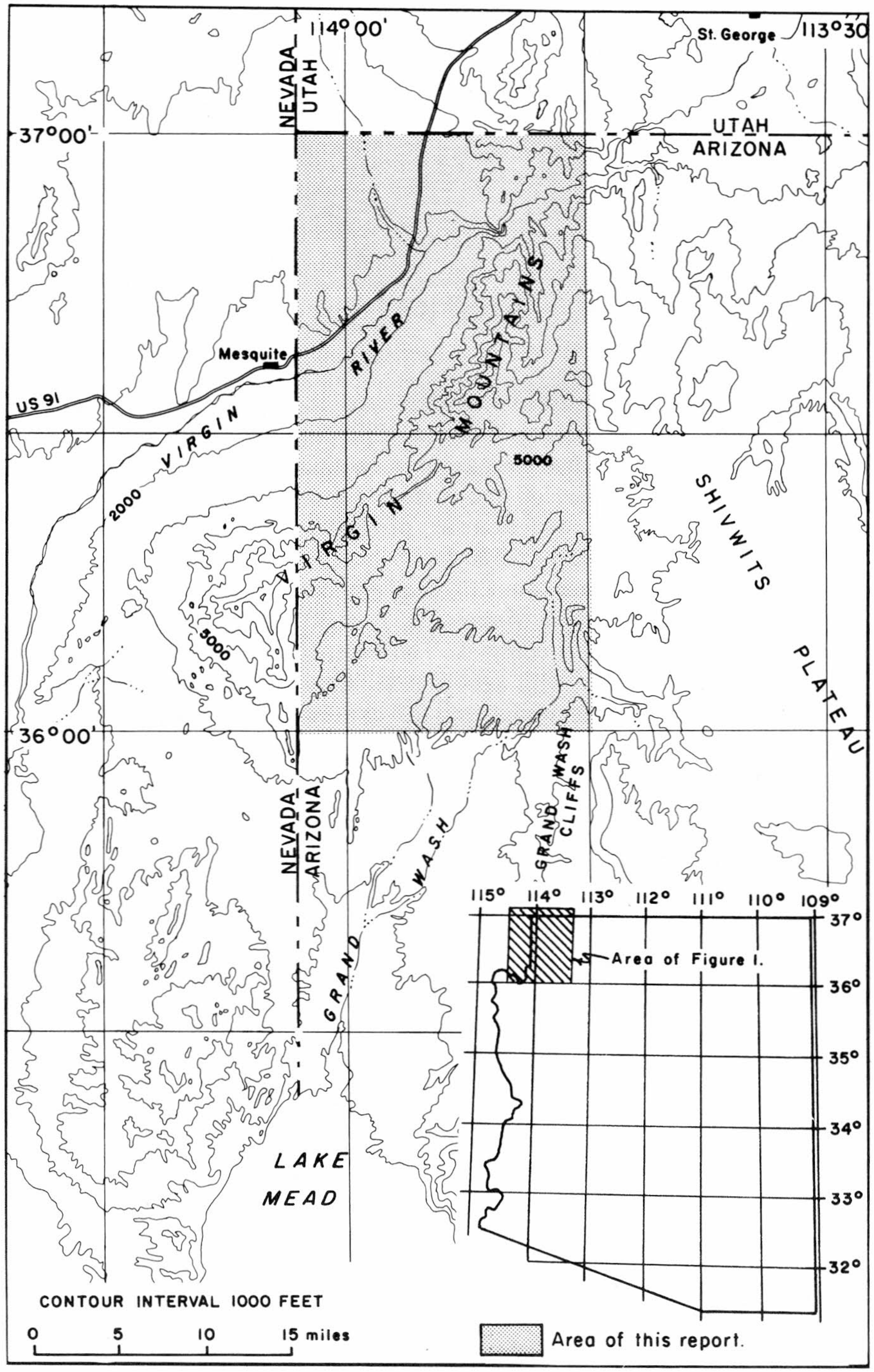


Figure 1. Map showing the location of the Virgin Mountains, Arizona.

INTRODUCTION

LOCATION AND SURFACE FEATURES

The Virgin Mountains with their northern extension, the Beaverdam Mountains, form an arcuate range, concave west-northwesterly, extending from southeastern Clark County, Nevada, northeasterly into Mohave County, Arizona, and thence northerly into Washington County, Utah. The portion of the range occurring in Arizona (Fig. 1) is shown on the U.S. Geological Survey Littlefield, Mesquite, Cane Springs, and Virgin Peak topographic quadrangle maps (Pl. I) and encompasses an area of approximately 600 square miles. A generalized map, showing the location of the principal named places within the mapped area. cited in the text, is shown as Figure 2.

The area lies on the eastern edge of the Basin-and-Range province, adjacent to the Plateau province. Maximum topographic relief is nearly 6,500 feet, with elevations ranging from 1,550 feet above sea level at the Virgin River to 8,012 feet at the summit of Mount Bangs.

Relief is relatively much steeper on the western flank of the range than to the east. Overlooking the Virgin River, slopes of 40 degrees and near vertical cliffs are common, whereas on the eastern flank, adjacent to the Plateau province, slopes average 15 to 20 degrees. Although the region is entirely within the Lower Colorado River Basin, Mount Bangs marks a local divide between drainage to the north and west to the Virgin River and drainage to the south, to upper Lake Mead, along Grand Wash and its tributaries.

Access to the area is afforded by U. S. Highway 91-Interstate 15 which connects with Las Vegas, Nevada, 80 miles to the southwest, and St. George, Utah, 30 miles northeast. Mesquite, Nevada, on Route 91, one mile west of the Nevada state line, is the local supply point for the few ranches and farms which occupy the irrigable lands along the Virgin River valley. Several graded roads and "jeep" trails fan into the mountains from Mesquite and serve as access for the ranchers who graze cattle at the higher elevations to the east.

The area has been actively prospected for mineral deposits but with only minor success. Small quantities of copper, manganese, and beryllium mineralization have been discovered but the only recorded commercial production has been 135 tons of manganese ore from Lime Kiln mine. In the period 1950-1955, uranium prospectors searched the region thoroughly but did not achieve any significant success.

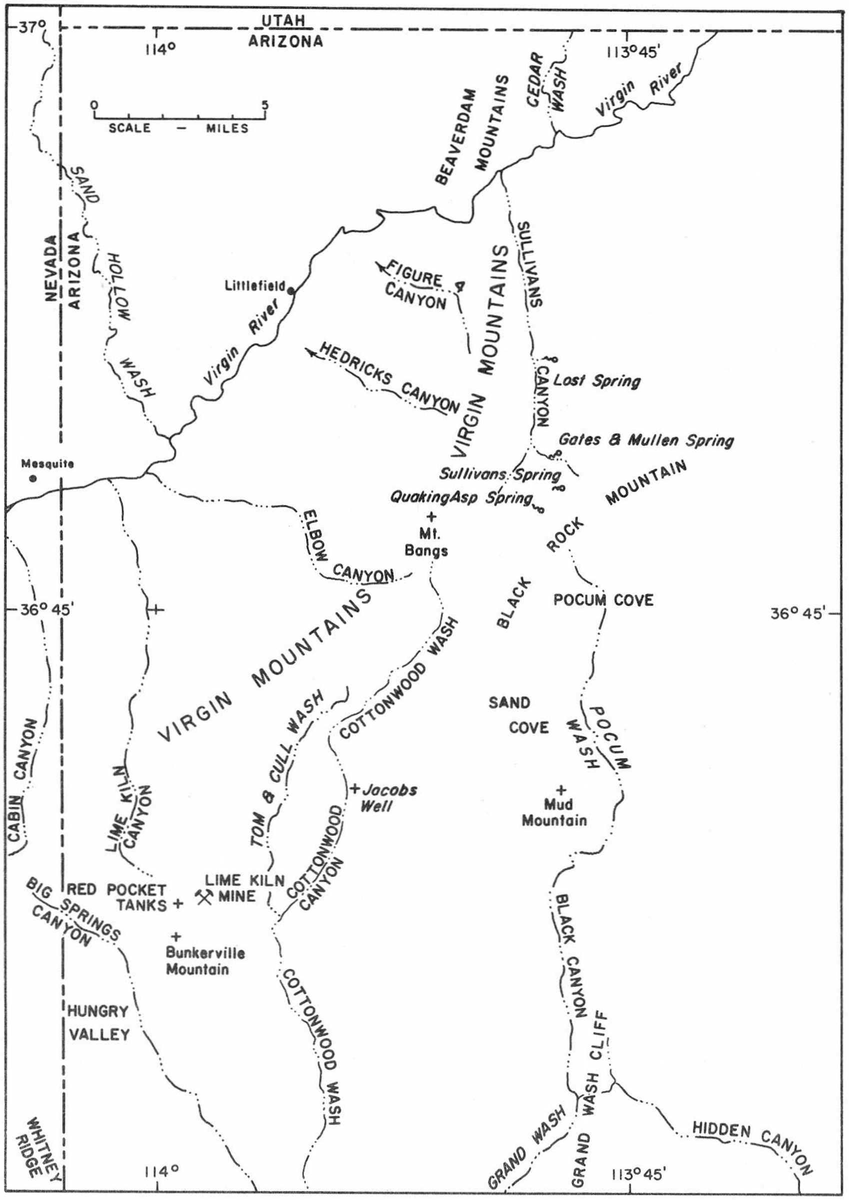


Figure 2. Map showing the location of the principal places mentioned in the text.

PREVIOUS STUDIES

Scientific explorations in northwestern Arizona were recorded by J. W. Powell as early as 1874. Marvine (1875)* and Gilbert (1875) reported

*See list of literature cited, page 65.

the results of reconnaissance studies made in conjunction with the Wheeler Survey. However, both the Powell and Wheeler surveys were primarily geographic in nature and the geologic studies were of necessity sketchy. Studies concerning the stratigraphy of the Plateau region were made by Walcott (1880, 1883) and later by Noble (1914, 1922). Some of the unit names assigned by these men are still in use.

With the exception of the very general map prepared by Gilbert, Marvine, and Howell (1876), no reliable geologic maps of the area were available until the Geologic Map of the State of Arizona was published (Darton *et al.*, 1924). Longwell (1928) extended his work in the Muddy Mountains, Nevada, into the Grand Wash area (Fig. 1) and briefly outlined the relations of the rocks there to those farther west.

In more recent years a number of studies of special problems have been made in this region. Stratigraphic studies have been made of the Cambrian System by McKee (1945) and Wheeler (1943), and of the Toroweap and Kaibab formations by McKee (1938). Correlations of the Paleozoic sediments have been made by McNair (1951) and Reeside and Bassler (1922). McKee (1954) published a detailed report on the stratigraphy of the Moenkopi Formation and more recently has made stratigraphic studies of the Redwall Limestone (McKee, 1960, 1963). A geologic map of Mohave County, Arizona, based on reconnaissance mapping, was published in 1959 by the Arizona Bureau of Mines (Wilson and Moore, 1959b).

PRESENT STUDY AND ACKNOWLEDGMENTS

The writer first became acquainted with the Virgin Mountains in 1957 while engaged in reconnaissance mapping for the Geologic Map of Mohave County, Arizona (Wilson and Moore, 1959b). The concept of a structural transition zone between the Colorado Plateaus and Basin-and-Range provinces in central Arizona had been developed (Wilson and Moore, 1959a) prior to that acquaintance and it was believed, after the brief examination in 1957, that both the geographic position and the observed structural characteristics of the Virgin Mountains made additional, detailed study of the range desirable with the view of determining if such a zone was present along this part of the provincial boundary. Although deformation of the type and degree known to occur in the Muddy Mountains, to the west (Longwell, 1928, 1949, 1962), was not observed, certainly the range is structurally more complex than the Plateaus, immediately adjacent to the east.

The original report was prepared and submitted in 1966 to the Department of Geology and the Committee on the Graduate Division of Stanford University, as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The field work upon which that report was based was done during parts of the field seasons from 1961 through 1965 and involved a total of approximately six months of field time. Based on additional field work during 1968 and 1970, a better understanding of some of the details of the stratigraphic record was developed, and these data have been incorporated in the present report.

Excellent base coverage is available for the area. Mapping was done on Army Map Service aerial photographs at a scale of approximately 1:60,000 and the data then were compiled on U. S. Geological Survey 15 minute series topographic sheets (Pl. I). These sheets, with a contour interval of 80 feet, were found to be sufficiently accurate to allow several areas requiring detailed mapping to be depicted directly on photographic enlargements of portions of the quadrangle sheets.

Grateful acknowledgment is due E. H. Moore and F. L. Stubbs who served ably as field assistants on several occasions and to Drs. S. N. Davis, J. D. Forrester, J. W. Harbaugh, B. M. Page, H. W. Peirce, and N. J. Silberling, Jr. who critically read the manuscript and made many helpful suggestions. The conclusions drawn and all errors, however, are the responsibility solely of the author. Finally, I wish to thank J. R. LaVoie, who most ably assisted in the drafting of several of the drawings.

STRATIGRAPHIC AND IGNEOUS RECORD

GENERAL STATEMENT

Rocks ranging in age from Precambrian to Tertiary are exposed in the Virgin and Beaverdam Mountains (Pl. I; Table 1). The Precambrian terrane consists of metamorphic and igneous crystalline rocks. The Paleozoic Era is represented by sedimentary formations deposited during the Cambrian, Ordovician(?), Devonian, Mississippian, Pennsylvanian, and Permian periods; the Mesozoic Era by the Moenkopi, Chinle, Moenave and Kayenta formations of the Triassic System and the Navajo Sandstone of Late Triassic(?) and Jurassic age. Two new units, the Jacobs Ranch Formation and the Cottonwood Wash Formation, are tentatively correlated with late Cretaceous(?) and early Tertiary rocks in eastern Nevada and southwestern Utah. Cenozoic deposits include the Muddy Creek Formation of Miocene(?) or Pliocene(?) age and volcanic flows and alluvial deposits of late Tertiary through Quaternary age.

The general distribution of the several formations is quite regular. Precambrian rocks are found along the western flank and in the central portion of the Virgin Mountains. Paleozoic and Mesozoic formations crop out as bands in normal sequence along the east flank of the range, roughly parallel to its axis, and Cenozoic deposits occur in the "basins" to either side of the divide formed by the mountain mass.

Numerous detailed stratigraphic studies, both of a regional nature (e.g., McKee, 1938, 1945, 1951, 1954, 1960, 1963; McNair, 1951; Reeside and Bassler, 1922; Wheeler, 1943) and of a local nature (e.g., Bissell, 1963; Langenheim, 1963; Longwell, 1928; Stokes, 1963) have been made of the Paleozoic and Mesozoic formations occurring in the Virgin Mountains. In these studies, however, the various workers have approached the area from diverse directions and, consequently, in some cases a variety of formational names have been applied to the same unit (Table 2). In such cases, in view of the proximity of the Plateau province and the relatively straightforward correlations possible between the Plateaus and the Virgin Mountains, the nomenclature common to the Plateau province has been given preference in this report.

To the degree that detailed reports on the stratigraphy of this area are available, only general descriptions, sufficient for an understanding of the structural relations, are given here and the reader is referred to the literature as cited above and in the Bibliography. A unit is discussed more fully in cases where it has not been discussed elsewhere, its correlation is in question, or it bears importantly on the solution of the structural history.

PRECAMBRIAN ROCKS

Crystalline rocks of Precambrian age form the foothills and lower slopes along the western flank of the range between Lime Kiln Canyon and Elbow Canyon. North of Elbow Canyon, the main mass of the Virgin Mountains, culminating at Mount Bangs and extending to Hedricks Canyon, is carved on similar rocks.

These crystalline rocks consist of a complex of high-grade metamorphic rocks intimately intruded by a variety of igneous rocks which are, in turn, more or less metamorphosed. The more conspicuous and widespread rock types include garnet-biotite gneiss, garnet-sillimanite-biotite schist, gneissic hornblendite, granite gneiss, granodiorite gneiss, amphibolite, and granitic and gabbroic intrusives. Locally, dikes and sills of a coarsely-crystalline, pink granite are abundant in the gneisses and these masses closely follow the grain of the gneissic banding. More or less concordant dike swarms of a light-colored pegmatite consisting of quartz, feldspar, and muscovite also are locally abundant in the metamorphic complex.

West of Lime Kiln Canyon garnet-biotite gneiss grades into garnet-sillimanite-biotite schist, the schistosity of which is essentially parallel to the foliation of the gneiss. Where occurring in the schist, pegmatite masses commonly contain minor amounts of beryl and chrysoberyl.

Table 1. Rocks of the Virgin and Beaverdam Mountains, Arizona.

AGE	FORMATION	THICKNESS (feet)	CHARACTERISTICS
Recent	Alluvium (not named)	Variable	Silt, sand, and gravel in stream deposits, fans, dunes, and terrace deposits.
		Unconformity	
Pleistocene(?) or Pliocene	Basin deposits (not named)	0 - 1,000+	Loosely to firmly consolidated silt, sand, and gravel. Caliche cappings common in Virgin River valley. Basalt flows intercalated with upper part at head of Grand Wash.
		Unconformity	
Miocene(?)	Muddy Creek Formation	0 - 500+	Playa deposits. Essentially flat-lying, thin-bedded, buff to pale red sand and silt. Locally includes evaporites.
		Angular unconformity	
Late Cretaceous(?) or Eocene(?)	Cottonwood Wash Formation	1,400+	Light gray, thin- to medium-bedded limestone above waterlain, gray-green tuff and a basal conglomerate of Paleozoic limestone fragments.
		Angular(?) unconformity	
Cretaceous(?)	Jacobs Ranch Formation	290±	Light-gray, pink-gray, and reddish-brown siltstone, sandstone and sandy conglomerate and a basal conglomerate of rounded chert and quartzite pebbles.
		Angular(?) unconformity	
Jurassic and Triassic(?)	Navajo Sandstone	2,500±	Strongly cross-bedded, brick-red sandstone. Lower part locally colored yellow to brown.
Triassic	Chinle, Moenave, and Kayenta Formations, undivided	1,500±	Red to maroon shale and thin-bedded sandstone. Contains petrified wood. Shinarump Conglomerate at base.
	Moenkopi Formation	1,600±	Upper member of red-brown gypseous shale; lower member of gray limestone, sandstone, and gypsum.

Table 1. Rocks of the Virgin and Beaverdam Mountains, Arizona. *(Continued)*

AGE	FORMATION	THICKNESS (feet)	CHARACTERISTICS
		Unconformity	
Permian	Kaibab Limestone (including Toroweap Formation)	750±	Two cliff-forming limestone members separated from each other and adjacent formations by soft, gypseous members.
	Hermit Formation	0 - 400±	Red to maroon, thin- to medium-bedded, flat-bedded fine sandstone and siltstone.
	Supai Formation	800 - 1,250±	Red to maroon, flat-bedded sandstone and yellow to pink, cross-bedded sandstone.
Permian and Pennsylvanian	Callville Limestone	1,350±	Thin- to medium-bedded, gray limestone; some cross-bedded sandstone units.
Mississippian	Redwall Limestone	600±	Medium-bedded to massive, dark gray limestone; considerable thin-bedded chert in lower half.
Devonian Ordovician(?) Cambrian	Undifferentiated	2,200±	Thin- to thick-bedded, light to dark gray limestone and dolomite.
Cambrian	Bright Angel Shale and Tapeats Sandstone	750±	500± feet of green and red shale overlying 250± feet of red to tan sandstone and quartzite.
		Unconformity	
Precambrian	not named		Crystalline metamorphic and igneous rocks.

Table 2. Paleozoic and Mesozoic nomenclature used in northwestern Arizona.

	I.A.P.G. (1963)*	McNair (1951)	McKee (1938, 1945, 1952, 1954, 1963)	Longwell (1946)	This paper	Reeside and Bassler (1922)
Jurassic	Navajo	—	—	Aztec	Navajo	(not named)
Triassic	Chinle	—	—	Chinle	Chinle	Chinle
	Shinarump	—	—	Shinarump	Shinarump	Shinarump
	Moenkopi	—	Moenkopi	Moenkopi	Moenkopi	Moenkopi
Permian	Kaibab	Kaibab	Kaibab	Kaibab	Kaibab	Kaibab
	Toroweap	Toroweap	Toroweap			
	Coconino	Coconino	Coconino	—	Coconino	Coconino
	Hermit(?)	Hermit	—	(red beds)	Hermit	Supai
	Queantoweap	Queantoweap	—		Supai	
	Pakoon	Pakoon	—			
Pennsylvanian	Callville	Callville	—	Callville	Callville	
	—	—	—	Bluepoint	—	
Mississippian	Yellowpine		Horseshoe Mesa			Redwall
	Arrowhead		—			
	Bullion	Rogers Spring	Mooney Falls (Redwall)	Rogers Spring	Redwall	
	Anchor		Thunder Springs (Redwall)			
	Dawn		Whitemore Wash (Redwall)			
Devonian	Sevy(?)	Muddy Peak		Muddy Peak		
Ordovician	Pogonip(?)	Pogonip(?)	Undivided		Undivided	Not
Cambrian	Undivided	Undivided				
	Peasley	Peasley	Muav			
	Chisholm	Chisholm		Undivided		
	Lyndon	Lyndon	Bright Angel		Bright Angel	
	Pioche	Pioche				Studied
	Prospect Mtn.	Prospect Mtn.	Tapeats		Tapeats	

* Intermountain Association of Petroleum Geologists: Guide book to the Geology of Southwestern Utah, 1963. List compiled from articles by individual authors (Bissell, 1963; Hintze, 1963; Langenheim, 1963; Stokes, 1963).

PALEOZOIC ROCKS

Tapeats Sandstone; Bright Angel Shale

The Tapeats Sandstone and the Bright Angel Shale, marine units of Early and Middle Cambrian age (McKee, 1945), are the lowermost Paleozoic units recognized in the Virgin Mountains.

Characteristically, the Tapeats crops out as a series of moderate cliffs and shallow benches rising above the rather smooth, rounded slopes developed on the underlying Precambrian crystalline rocks. It consists of approximately 250 feet of sandstone and quartzite of which the lower one-third is composed of brick-red to maroon, thin- to medium-bedded sandstone. The upper two-thirds is composed of buff to light-gray, thick-bedded, predominantly cross-bedded sandstone and quartzite.

McNair (1951, p. 509) reported 523 feet of Chisholm Shale, Lyndon Limestone, and Pioche Shale on Whitney Ridge in the Virgin Mountains, Nevada (Fig. 2), which he correlates with the Bright Angel Shale (McNair, 1951, Fig. 2). This sequence, which consists of olive-green to reddish-brown, thin-bedded, fissile shale and massive limestone is easily recognized above the Tapeats Sandstone, where it forms smooth but rather steep slopes as a result of the protection afforded it by the overlying, comparatively resistant carbonate rocks.

Cambrian-Devonian Carbonate Rocks

In the Virgin Mountains a thick series of marine limestones and dolomites, containing minor beds of conglomorate, occupies the interval between the Cambrian Bright Angel Shale and the Redwall Limestone of Mississippian age. McNair (1951) describes this series as it appears in Whitney Ridge. Here, he measured 2,211 feet of carbonate rocks which he subdivided to include 791 feet of Peasley Limestone, 652 feet of undifferentiated Cambrian dolomitic limestone, 216 feet of Pogonip(?) Limestone (Ordovician), and 552 feet of Devonian Muddy Peak Limestone.

These rocks crop out in the cliffs that extend from Lime Kiln Canyon north, along the west flank of the range, to the head of Elbow Canyon and in the north-plunging nose of the Virgin Mountain anticline, near Figure 4 Canyon. In overall appearance these formations have few distinguishing characteristics and no attempt was made to separate them (Pl. V).

Mississippian System

The Mississippian System is represented in the Virgin Mountains by cherty limestones of marine origin. The nomenclature applied to these rocks has been varied. McNair (1951, p. 518) correlated 577 feet of Mississippian rocks on Whitney Ridge with the Rogers Spring Limestone

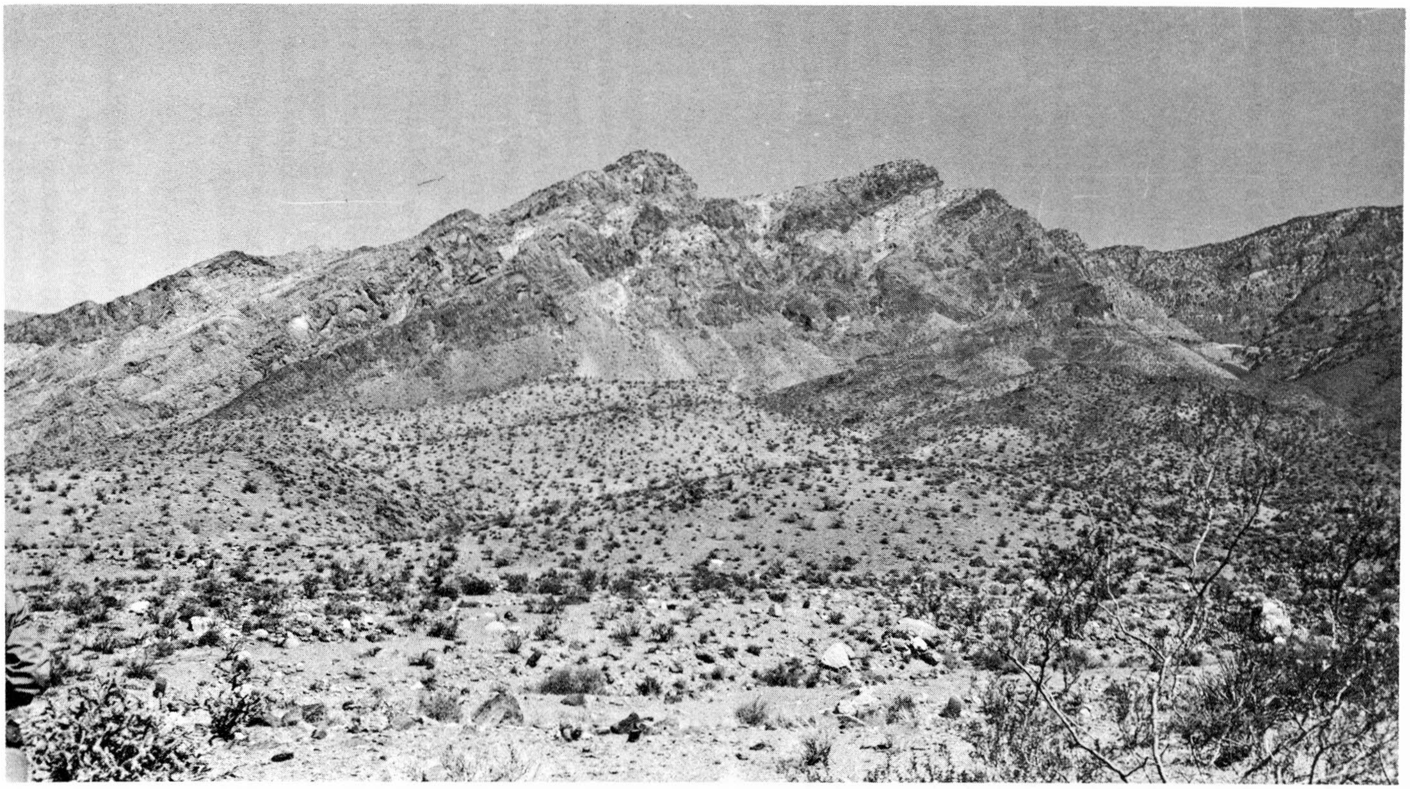


Plate V. Cambrian, Ordovician(?), and Devonian rocks near the northern end of Virgin Mountain Anticline (see Plate IV for location and orientation of photographic plates).

in the Muddy Mountains. Langenheim (1963, Fig. 2) reported 90 feet of Anchor Limestone, 256.5 feet of Bullion Limestone, 10 feet of Arrowhead Limestone, and 80 feet of Yellowpine Limestone in the "Virgin Mountains Approx. Sec. 5, T.38N., R.16W., Mohave Co., Ariz." Unfortunately, this places the measured section in an area of valley fill, five miles from the nearest outcrop of Mississippian rocks, and it is, therefore, difficult to verify.

The Redwall Limestone has been traced west continuously from the type-section in eastern Grand Canyon, past Whitmore Wash where sections have been measured by McKee (1963), to the Grand Wash Cliffs, within 20 miles of the Virgin Mountains (R. T. Moore, 1958, M. S. Thesis, Univ. Ariz.). Two of the four members described by McKee (1963), the Thunder Springs and Mooney Falls members, are particularly distinctive in the Virgin Mountains.

The Thunder Springs Member consists of about 100 feet of alternating, thin bedded limestone and chert which form a striking pattern, much resembling railroad tracks in a marshalling yard. This is the first stratigraphic unit above the Bright Angel Shale distinctive enough to be recognized from cursory examination and it is an excellent marker horizon.

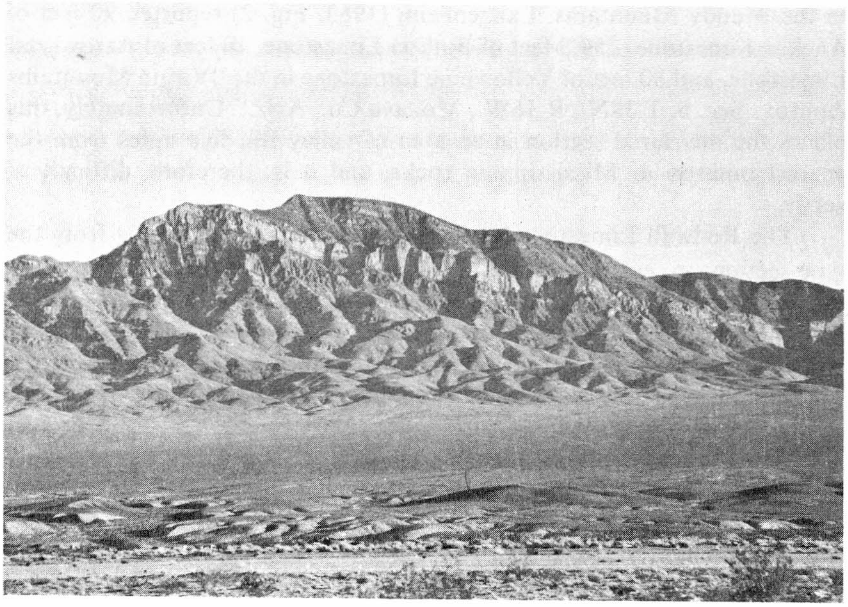
The Mooney Falls Member of the Redwall Limestone consists of over 200 feet of massive, cliff-forming light gray limestone overlying the Thunder Springs Member. It is equally distinctive and can be recognized even at moderately great distances (see Pl. VI).

Although the individual members of the Redwall Limestone can be distinguished readily, no attempt was made to separate them on the geologic map (Pl. I). The Redwall Limestone tends to crop out in cliffs, thus the entire formation forms only a narrow band at the map scale (Pl. I).

Pennsylvanian and Permian Systems

Principal formations of Pennsylvanian and Permian age, as recognized in this report, include: the Callville Limestone of late Pennsylvanian-early Permian age; the Supai and Hermit formations which consist of clastic rocks of Permian age; and the Toroweap and Kaibab formations which consist predominantly of marine carbonate rocks of Permian age.

The Callville Limestone (Longwell, 1928, p. 32) was originally defined to include rocks of both Pennsylvanian and Permian age. McNair (1951, p. 524) proposed the name Pakoon Limestone for the Permian portion of the formation, restricting the term Callville to the Pennsylvanian beds. The absence of a mappable contact between the two units, however, has dictated the use of the older, broader definition of Longwell.



A. Telephoto view southeast toward steep west flank of Virgin Mountains. Light colored band is Mooney Falls Member.

B. View east, up Virgin Narrows, at cherty Thunder Springs Member (foreground) and massive Mooney Falls Member.

Plate VI. Redwall Limestone (see Plate IV).

Nearly 1,400 feet of Callville Limestone, a marine deposit consisting primarily of thin- to thick-bedded, interbedded limestone and dolomitic limestone, crops out in the Virgin Mountains. Locally, lenses of pink to tan chert and medium-bedded units of cross-bedded pink sandstone are common. The formation weathers pink-gray, tan-gray, and dark gray and forms steep slopes broken by low cliffs.

Near the head of Cedar Wash, in Sections 3 and 10, T.41 N., R.14W. (Pl. I; Fig. 5), up to 200 feet of gypsum interbedded with minor amounts of sandstone and limestone crop out over an area of nearly three-quarters of a square mile above medium-bedded limestone assigned to the Callville. This gypsum unit is also assigned to the Callville and is assumed to represent evaporite deposits formed during the retreat of the Callville sea to the west. Its actual extent is unknown as it passes under the overlying Supai Formation to the north and east and has been removed by erosion to the south and west.

The contact between the Callville and the overlying Supai Formation is sharp and the change in lithologies is abrupt. In contrast with the predominantly carbonate composition of the Callville, the Supai consists of massive-bedded, flat-bedded to cross-bedded sandstone ranging in color from buff-yellow through pink to dull red. In Bunkerville Mountain it is approximately 800 to 900 feet thick.

In the southern part of the area the Supai Formation is overlain by the Hermit Formation. This unit is well displayed in Grand Wash Cliff in the vicinity of Hidden Canyon, and in Bunkerville Mountain near Red Pockets Tanks. It consists of thin-bedded, dark-red and brownish-red, fine-grained sandstone interbedded with medium-bedded, lighter colored sandstone.

In Bunkerville Mountain the Hermit Formation is approximately 400 feet thick. It rapidly thins to the north, however, and is not recognized above the Supai that crops out in Sullivans Canyon. The Supai Formation, on the other hand, thickens to the north and the aggregate thickness of these two clastic units is quite constant throughout the area, measuring between 1,200 and 1,300 feet.

The youngest Paleozoic rocks in northwestern Arizona are contained in the Toroweap and Kaibab formations of Leonardian age. The Toroweap Formation was defined by McKee (1938, p. 12) who restricted the name Kaibab Formation to the upper portion of the Kaibab Limestone as originally defined by Darton (1910). Although the subdivision is certainly valid, the distribution and spatial relations of the two formations are such that it seems more convenient to map the two as a single unit, and the older usage of the term Kaibab Limestone is therefore retained in this paper.

As exposed in the Virgin Mountains, the undifferentiated Kaibab Limestone consists of two thick-bedded to massive, cliff forming, dark-gray limestone units separated from each other and from overlying and underlying formations by soft, slope-forming gypsiferous, and in some places, marly, red-bed units. The total thickness of the formation is nearly 750 feet.

The Kaibab Limestone, with its characteristic profile of alternating slopes and cliffs, is one of the more distinctive units in the Virgin Mountain area, and serves as an excellent stratigraphic marker.

MESOZOIC ROCKS

Triassic and Jurassic Systems

Rocks of known Mesozoic age present in the Virgin Mountains are sedimentary in origin and include the Moenkopi Formation of Early and Middle(?) Triassic age; the Chinle, Moenave, and Kayenta formations, undivided, of Late Triassic age; and the Navajo Sandstone of Late Triassic(?) and Early Jurassic age. With the exception of the basal member of the Moenkopi Formation, these rocks are all of continental origin.

The Moenkopi Formation consists of two members and has an aggregate thickness of nearly 1,600 feet. The lower unit, which composes approximately one-third of the thickness of the formation, is of marine origin. It consists of gray to buff limestone in beds ranging from a fraction of an inch to two feet in thickness, interbedded with gray, yellow, and red, thin- to medium-bedded sandstone and thinly laminated shale, and thin-bedded gypsum. The overall color of the lower member is light greenish gray. The upper unit, of continental origin, is composed of thin-bedded, brick-red to chocolate-brown sandstone and silt-stone.

The Moenkopi Formation is unconformably overlain by the Shinarump Conglomerate, the basal member of the Chinle Formation. The Shinarump consists of 30 to 75 feet of yellow to brown, thin- to medium-bedded, cross-bedded sandstone and conglomerate (Pl. VII). Graded-bedding is common in the individual laminae of cross-bedded sets, the coarser material consisting of well-rounded and frosted chert pebbles up to 1 inch in diameter. The Shinarump is considerably more resistant than either the underlying Moenkopi Formation or the overlying Chinle "shales." Consequently, it forms distinctive hogbacks and ledges and is an easily recognized and useful marker bed.

Above the Shinarump Conglomerate lie some 1,500 feet of brick-red to maroon, thin-bedded shale, siltstone, and fine-grained sandstone. Small, bleached, white spots up to half an inch in diameter are common throughout the sequence and beds of gypsum and masses of petrified wood are locally abundant. This 1,500 feet includes 400 to 500 feet of sediments

Plate VII. Overturned Shinarump Conglomerate at the head of Sullivans Canyon (see Plate IV).

belonging to the Petrified Forest Member of the Chinle Formation unconformably overlain by approximately 1,000 feet of rocks belonging to the Moenave and Kayenta formations, undifferentiated. Although the Moenave and Kayenta formations belong to the Glen Canyon Group, and elsewhere are more or less easily distinguishable from the Chinle Formation, on the basis of the uniform lithologic character of the sequence in this area, the entire 1,500 feet of sediments is depicted as a single unit on the geologic map (Pl. I) and referred to as the Chinle Formation.

The Navajo Sandstone overlies the Chinle Formation, as considered here. It consists of up to 2,500 feet of predominantly orange-red, conspicuously cross-bedded sandstone. Locally, however, the lower 200 to 300 feet of the formation is white, yellow, or brown. Cross-bedding is of the trough type and individual sets range from 2 feet to more than 20 feet in thickness and foreset lengths range up to 100 feet.

Longwell (1949, p. 931) correlated this formation in the Muddy Mountains, Nevada, 40 miles to the west, with the Aztec Sandstone occurring in the Goodsprings Quadrangle, Nevada (Hewitt, 1931). The Aztec and Navajo, however, are correlative (Baker *et al.,* 1936) and it is felt that the name Navajo is to be preferred in this area in view of the proximity of typical Navajo Sandstone sections to the northeast (Wright and Dickey, 1963; Wilson, 1965).

Cretaceous(?) System

The Jacobs Ranch Formation crops out on the east side of Tom-and-Cull Wash in low hills and along the base of the ridge which separates Tom-and-Cull and Cottonwood washes. It is herein named for the principal ranch in the area of outcrop. The weathered formation forms a hummocky terrain of reddish-brown to pale-yellow, sandy slopes, and swales containing light-gray to buff, silty soil. Its known present extent is restricted to a band approximately 4 miles long and up to 1,000 feet in width in unsurveyed sections 5, 6, and 7, T.37N., R.15W., and in surveyed section 32, T.38N., R.15W. (Pl I).

The age of the Jacobs Ranch Formation is Cretaceous(?). It unconformably overlies the Navajo Sandstone and in turn is overlain unconformably by the Cottonwood Wash Formation of Late Cretaceous(?) to Eocene(?) age.

The contact between the Navajo Sandstone and the Jacobs Ranch Formation is poorly exposed, in most places being concealed beneath loose, wind-blown sand. However, where the bottom of the Jacobs Ranch Formation is visible, it is marked by a basal conglomerate ranging from 5 feet to 20 feet in thickness which rests on a surface of slight relief carved on the Navajo Sandstone. It was not possible to determine with certainty the degree, if any, of angular unconformity that might exist between the two formations because of the strong cross-bedding in the Navajo. Based on the parallelism of the outcrop patterns of the two formations, however, and the similarity in dip of the upper and lower contacts of the Navajo Sandstone, it can fairly be assumed that any angular unconformity between the units is slight.

The basal conglomerate of the Jacobs Ranch Formation is overlain by up to 285 feet of clastic sediments consisting of light-gray to pink-gray siltstone; reddish-brown, thin-bedded, sandy siltstone with some interbedded 1 to 2 foot beds of massive yellow-brown sandstone; and, in the lower half of the formation, buff to gray, silty sandstone, locally cross-bedded, containing a few thin, chert-pebble conglomerate beds.

The Jacobs Ranch Formation displays considerable variability of composition along strike, but the stratigraphic section measured approximately in unsurveyed section 7, T.37N., R.15W., is representative.

No direct evidence for the age of the Jacobs Ranch Formation was found. Based on its stratigraphic position and lithologic character, it is probably equivalent to a portion of the Upper Cretaceous(?) Iron Springs Formation (Mackin, 1947, p. 7) of southwestern Utah, which in turn has been correlated by Bissell (1952, Fig. 3) with the Willow Tank Formation and Baseline Sandstone (Longwell, 1949, p. 931) which occur in the Muddy Mountains, Nevada, some 40 miles to the west.

Cretaceous(?) or Tertiary System

Above the Navajo Sandstone and Jacobs Ranch Formation is a thick sequence of sediments which are herein named the Cottonwood Wash Formation of Late Cretaceous(?) or Eocene(?) age. The formation includes a well indurated basal conglomerate overlain by poorly consolidated, water-lain tuff, which, in turn, is overlain by limestone. It is named for Cottonwood Wash, where over 1,400 feet of the sequence is exposed in the ridge on the west side of the wash, approximately in unsurveyed section 18, T.37N., R.15W.

Typically, the basal conglomerate consists of pebbles and cobbles of the more resistant Paleozoic limestones embedded in a hard matrix of calcium carbonate cement and quartz sand, the sand probably having been derived from the underlying Jurassic Navajo Sandstone. The limestone fragments are for the most part subangular to rounded and average from 2 to 3 inches in maximum dimension. The conglomerate attains its maximum thickness of approximately 50 feet near where the road between Lime Kiln mine and Jacobs Well crosses the formation, and here it is a distinctive cliff-forming unit beneath the softer, tuffaceous beds of the middle unit. Both to the north and south, however, the basal conglomerate thins and it is absent in the exposures of the Cottonwood Wash Formation north of Jacobs Well and those southeast of Hungry Valley.

Stratigraphic section of the Jacobs Ranch Formation Tom-and-Cull Wash

Feet

Cottonwood Wash Formation:
 Limestone cobble conglomerate

Unconformity.

Jacobs Ranch Formation:

10. Mostly covered. The sparse outcrops are yellowish-tan, flat-bedded sandstone. Bedding ranges in thickness from ½ to 2 ft. Surface cover consists of loose, tan, sandy silt containing numerous black and yellow chert pebbles. 28
9. Covered. Surface material consists of loose, gray-buff, clayey calcareous soil containing many black, red, and yellow pebbles. 65
8. Sandstone, silty, pale- to medium-red, consisting of well-rounded to elongate, frosted quartz grains, 0.1 to 0.25 mm., cemented with iron oxides. Bedding poorly defined, but mainly flat-bedded with locally cross-bedded zones 1 to 2 feet thick in which the laminae range from ½ to 2 in. in thickness. Locally grades into lenses of pebble conglomerate consisting of chert and rock fragments up to 1 in., in sand matrix. Unit is mostly poorly cemented and appears to have moderate porosity. 62
7. Sandstone, white to light-gray, well cemented, consisting of rounded quartz and chert grains, 0.1 to 0.5 mm., in a hard, carbonate cement. Cross-bedded laminae ½ to 1 in. thick. 10
6. Conglomerate, smooth, well-rounded to elongate pebbles, ¼ to 3 in., occasional cobbles to 6 in. Fragments consist of small, black, red, and occasionally yellow chert pebbles, and cobbles of light- to dark-gray limestone and light-gray to pale-yellow quartzite. Matrix like unit 7. 2
5. Like unit 7. 4
4. Like unit 6. 6
3. Sandstone, pale-pink to gray, consisting of well-rounded, frosted quartz grains, 0.1 to 0.25 mm., poorly cemented. Cementation of a clay-like nature. Massive-bedded to thin-bedded at top. Contains some chert and rock fragments up to 2 in. near top. Pebbles, light-gray to pale-yellow. 10
2. Like unit 8. 82
1. Basal conglomerate consisting of smooth, rounded chert pebbles, ¼ to 3 in., red, yellowish-olive to gray, with occasional cobbles of white, gray, and yellow quartzite and rare cobbles of light- to dark-gray limestone. Matrix like unit 8. 18

 Total Jacobs Ranch Formation 287

Unconformity

Navajo Sandstone:
 Sandstone, orange-red to pink, large-scale cross-bedding.

The middle member of the formation grades upward from the basal conglomerate and reaches a maximum thickness of approximately 600 feet. It consists of thin, flat-bedded, water-lain tuff interbedded with layers of altered, bentonitic material which swells and slakes when soaked in water. The tuff ranges from beds of fine, white ash to beds composed of coarse sand-sized particles consisting mainly of quartz, biotite, and devitrified glass shards. In some beds, small pebbles of chert are abundant and graded bedding is conspicuous. Locally, lenses and irregular masses of jasper and common opal are present. The altered, bentonitic layers are megascopically devoid of internal structures, other than shrinkage cracks. They appear to be composed of a dense, massive material, with a distinctive, light green color, which imparts a pale gray-green tint to the entire member.

The upper member, which consists of thin- to medium-bedded limestone, is in excess of 700 feet thick. The limestone is variously fine-grained and pulverulent, hard and dense, or, and as is most typical, very vuggy and porous. On fresh surfaces, the rock is very light in color, ranging from light gray to white. Weathered surfaces are usually rough and deeply pitted and have a gray to gray-buff color. This unit is quite resistant to weathering and stands as a hogback, extending from near Hungry Valley northeast to the west side of Sand Cove.

The Cottonwood Wash Formation rests on the underlying Jacobs Ranch Formation and Navajo Sandstone with angular unconformity as evidenced by the fact that the Jacobs Ranch Formation is truncated both to the north and south, where the Cottonwood Wash Formation rests directly on the Navajo. The degree of angular discordance is quite variable, however, ranging from as little as 3° to 5° in the vicinity of the Jacobs Ranch measured section to as much as 10° to 15° near the southern extent of the Jacobs Ranch Formation.

An accurate age determination for the Cottonwood Wash Formation would be extremely helpful in unravelling the chronology of the structural history of the Virgin Mountains, as this sequence is the youngest recognized to have been involved in the prominent easterly tilting to which a large part of the range has been subjected. Unfortunately, however, very little evidence was found for dating the Formation. Rather intensive search for fossils proved futile and it is therefore necessary to fall back upon relatively unreliable lithologic correlations over rather great distances.

In the Muddy Mountains, Nevada, 40 miles to the west, the sequence consisting of the Overton Fanglomerate and the Horse Spring Formation of Cretaceous(?) or Tertiary(?) age (Longwell, 1928, 1949) occupies the same stratigraphic position and is quite similar to the Cottonwood Wash Formation. In the Pine Valley Mountains, near St. George, Utah, the Claron Formation of Upper Cretaceous(?) -Eocene age (Cook, 1957, p. 38) is grossly similar in lithology, depositional history, and stratigraphic position. Thus, the Cottonwood Wash Formation is tentatively correlated with these formations.

CENOZOIC ROCKS

Deposits of known or inferred Cenozoic age are by far the most widespread of the units mapped, constituting fully two-thirds of the exposures in the area. These units range from Miocene(?) to Recent in age and consist of basalt flows and lake, stream, terrace, and fan deposits.

The oldest of these units is the Muddy Creek Formation which Longwell (1949, p. 929) provisionally assigned to the upper Miocene(?) or lower Pliocene(?) Epoch. Although outcrops are limited to a few exposures in the walls of Sand Hollow Wash and to an area of badlands in the extreme northwest corner of the area, the Muddy Creek Formation underlies the thin, surficial gravels and accounts for the bulk of the fill in the intermontane Virgin River valley.

The Muddy Creek Formation consists of cream to light-brown, thin- to medium-bedded clay, sand and silt. Locally, cross-bedding is conspicuous and beds of gypsum are common. Deposition probably took place under intermittent lacustrine conditions.

A deposit which, because of its lithologic similarity and stratigraphic position, is correlated with the Muddy Creek Formation crops out in the walls of Cottonwood Canyon, south of Jacobs Well. It consists of thin- to medium-bedded silt and sand with occasional beds containing small chert pebbles. The predominant color of the unit is yellow to buff but locally it has a distinct red color, reflecting the color of the Navajo Sandstone which crops out nearby and was an important local source of material.

In Cottonwood Canyon the Muddy Creek Formation is essentially flat-lying although dips of up to 5 degrees are developed in areas of local warping. The formation overlies the easterly dipping Cottonwood Wash Formation with angular unconformity and is in turn unconformably overlain by a coarse conglomerate which forms the base of a thick sequence of poorly consolidated sand and gravel.

In the Virgin River valley the Muddy Creek Formation is overlain by extensive surficial deposits which consist of conglomerate capped by caliche. The caliche, which is quite hard and resistant to erosion, is, in fact, largely responsible for the preservation of the Muddy Creek Formation to its present extent in the Virgin River valley. These two units are well exposed in the Littlefield area and together are informally designated the "Littlefield Formation."

In the Cottonwood Wash area, the unconformity between the Muddy Creek Formation and the overlying gravels marks an episode of considerable erosion. Deep channeling, extensive terracing, and, in places, complete stripping of the Muddy Creek Formation was effected by streams which apparently headed in the Hungry Valley-Lime Kiln mine area. Subsequently, the channels were filled by the overlying gravels which ultimately completely covered the Muddy Creek Formation. These gravels can now be traced to the south, down Grand Wash, at least to the

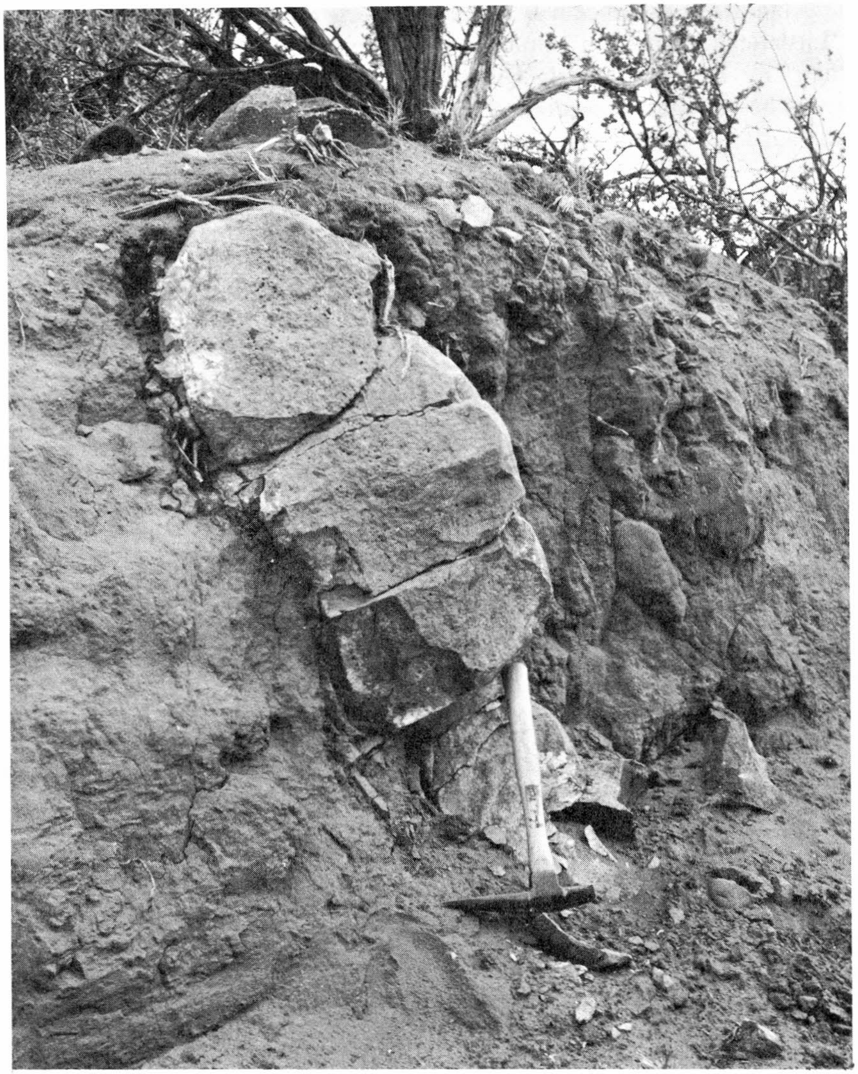


Plate VIII. Basalt dike intruding Cenozoic basin deposits near Sand Cove (see Plate IV for location and orientation).

Colorado River, and to the east, to Grand Wash Cliff, where they were deposited against the cliff face. In the vicinity of Mud Mountain, basalt flows are intercalated with the upper part of these deposits and form the surface of much of the area over which the gravels are distributed.

The intercalated basalt flows were extruded at several centers, notably at Mud Mountain, Black Rock Mountain, and Mosby Peak. Significant outpourings also probably occurred from numerous dikes, such as those now exposed by erosion near Sand Cove (see Pls. I, VIII).

No direct evidence was found for dating either these deposits, or the "Littlefield Formation" flooring the Virgin River valley, more closely than late Tertiary to early Quaternary.

The youngest deposits in the area consist of Recent stream gravels, alluvial fans, and talus cones.

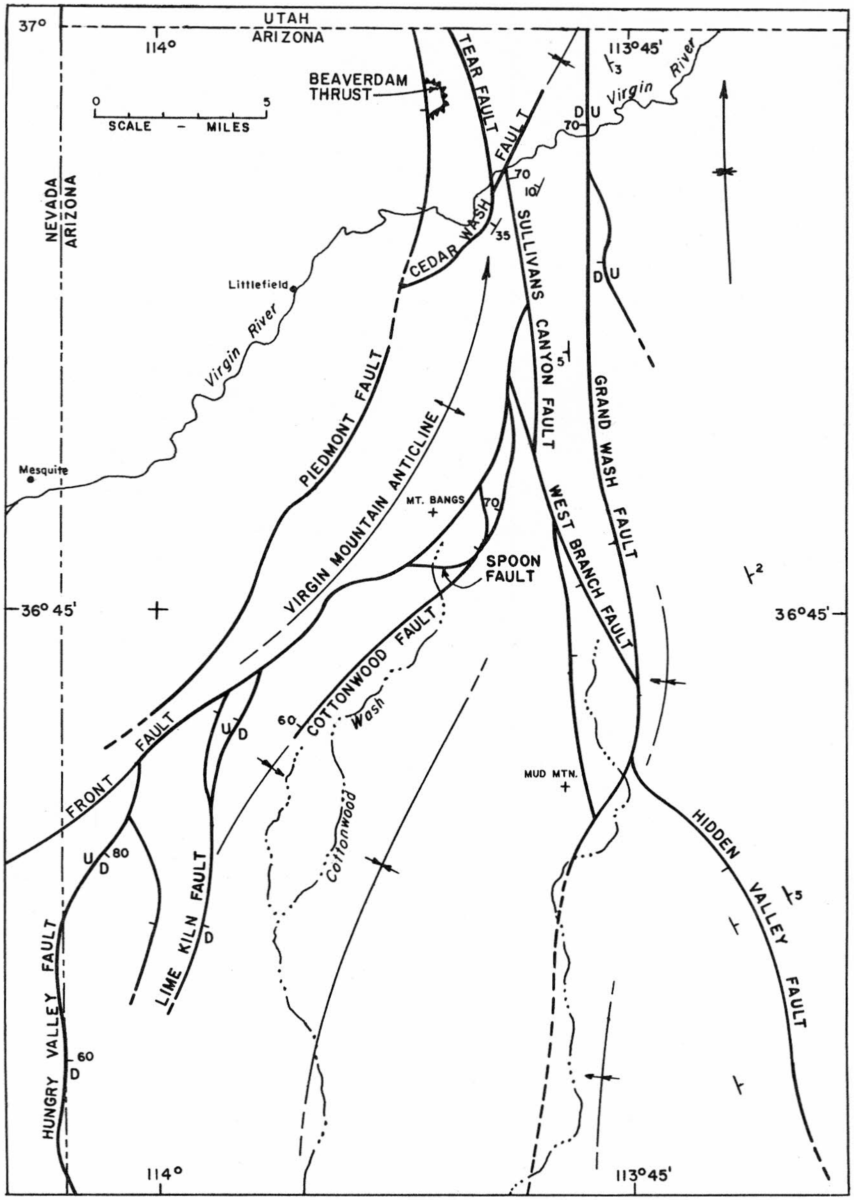


Figure 3. Structure diagram of the Virgin and Beaverdam mountains.

STRUCTURAL RECORD

GENERAL STATEMENT

Structural elements (see Fig. 3) that have played a major part in the development of the Virgin and Beaverdam Mountains, Arizona, include a large anticlinal fold and a zone of reverse faulting that extends for nearly 20 miles along the eastern flank of the range.

The basic pattern established by these structures has been modified by high-angle faults of large displacement which strike substantially parallel with the line of reverse faulting, and by transverse faults of less displacement.

In the northern part of the range low-angle thrust faulting is locally conspicuous.

VIRGIN MOUNTAIN ANTICLINE

The anticlinal character of the northern part of the Virgin Mountains is clearly shown on the geologic map (Pl. I) by the attitudes of the Paleozoic rocks that crop out immediately north of the central mass of Precambrian rocks.

The axis of this large fold, which here is named the Virgin Mountain anticline, trends N.30°E. throughout most of its length but veers to N.10°E. at its northern end. It can be traced easily along the spine of the range from Elbow Canyon, north through Mount Bangs, to the vicinity of the confluence of Sullivans Canyon and Virgin River.

Near its northern end the axis plunges rather abruptly to the north as reflected by the change in attitude of the sedimentary rocks in that direction. Along the east flank of the fold, the Paleozoic rocks, although offset by considerable faulting, crop out in roughly parallel, east-dipping bands. Toward the north, their strike swings from north, progressively through west, to nearly southwest in the Figure 4 Canyon area (see Pls. V, IX, and X), forming a broad nose across the axis.

The angle of dip also varies across the nose thus formed by the sedimentary rocks. In the west limb the rocks dip from 30° to 60°NW. and across the axis from 10° to 20°N. In the east limb, near the northern end, dips of 35°E. are average. Farther south, up Sullivans Canyon, steeper dips are encountered, but these are in part a reflection of faulting in that region.

Plate IX. View southwest, across Sullivans Canyon, of east flank of Virgin Mountain anticline. Precambrian rocks on middle skyline (see Plate IV).

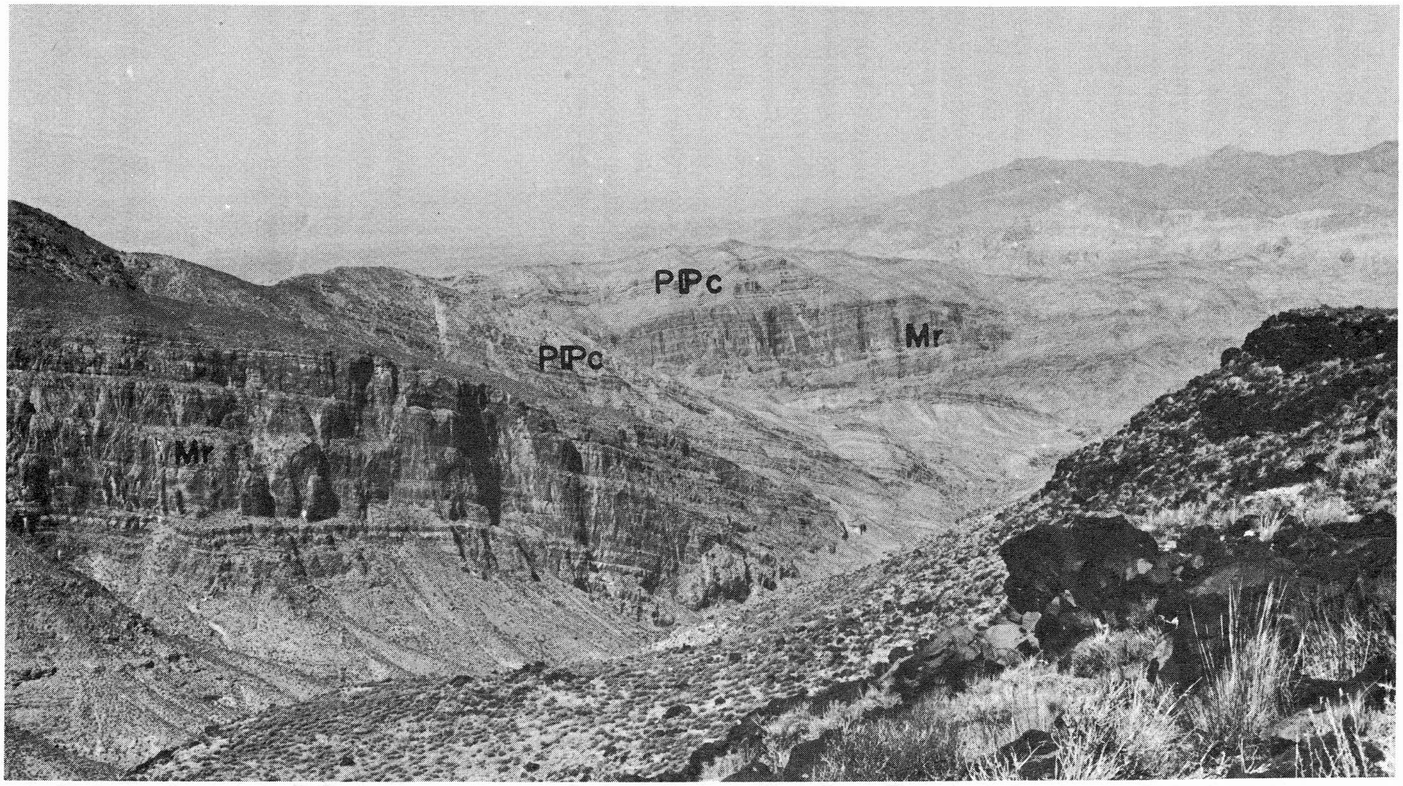


Plate X. View northwest across Sullivans Canyon. East flank and north-plunging nose of Virgin Mountain anticline in foreground and Beaverdam Mountains in middle distance and on the right-hand skyline. PIPc, Callville Limestone; Mr, Redwall Limestone (see Plate IV).

Between Figure 4 Canyon and Hedricks Canyon, high-angle reverse faulting has locally brought older rocks up against younger rocks (Pl. I; Pl. II, sections E-E', F-F'; Pl. XIII). In this area, in the hanging wall blocks, the rocks dip as steeply as 75°NW. (see Pl. XIIIA).

Between Hedricks Canyon and Elbow Canyon, the cover of Paleozoic rocks has been stripped from the crest and the west flank of the Virgin Mountain anticline, exposing the core of Precambrian crystalline rocks. However, westerly dipping sedimentary rocks are believed to be preserved under the Cenozoic deposits at the western base of the range, presumably having been faulted down to that position along Piedmont fault (see Pl. II, sections E-E', F-F', G-G').

The anticlinal nature of the range has been highly modified by faulting south of Elbow Canyon, and most of the Paleozoic sedimentary rocks, in which the folding is well displayed to the north, have been removed by erosion. The only remnants of the once extensive sedimentary shell of the fold are easterly dipping rocks in the east limb of the anticline which extends to the southwest, to Lime Kiln Canyon.

These east-dipping rocks also form the west limb of a syncline which is situated west of Grand Wash Cliff and extends south from Pocum Cove (see Pl. I; Pl. II, section M-M'; Pl. XXII). Although the axis of the synclinal fold is concealed beneath the flat-lying Muddy Creek Formation and younger units, its general position may be inferred from the position and dip of its limbs. As noted above, the west limb of the syncline is exposed along the southeast flank and the crest of the range, between Elbow Canyon and Lime Kiln Canyon. The position of the east limb is marked by west-dipping Paleozoic and Mesozoic rocks which strike essentially north-south and crop out near the east edge of the area (Pl. I). The southern extent of the synclinal fold is unknown.

REVERSE FAULTING

Reverse faulting has been important in the building of the Virgin and Beaverdam Mountains and it is manifested as both low-angle overthrust faulting and high-angle reverse faulting. In the northern part of the area, the Beaverdam thrust fault is locally conspicuous. In the central reaches of the range, Cedar Wash fault and Cottonwood fault, two high-angle reverse structures, are of major consequence.

Beaverdam Thrust Fault

In the Beaverdam Mountains, thrust faulting has occurred along the west flank of the range near the Utah state line. The relations of this faulting are shown in the photographs (Pls. XI, XII), on the detailed geologic map (Fig. 4), and diagramatically on structure sections A-A' and B-B' (Pl. II).

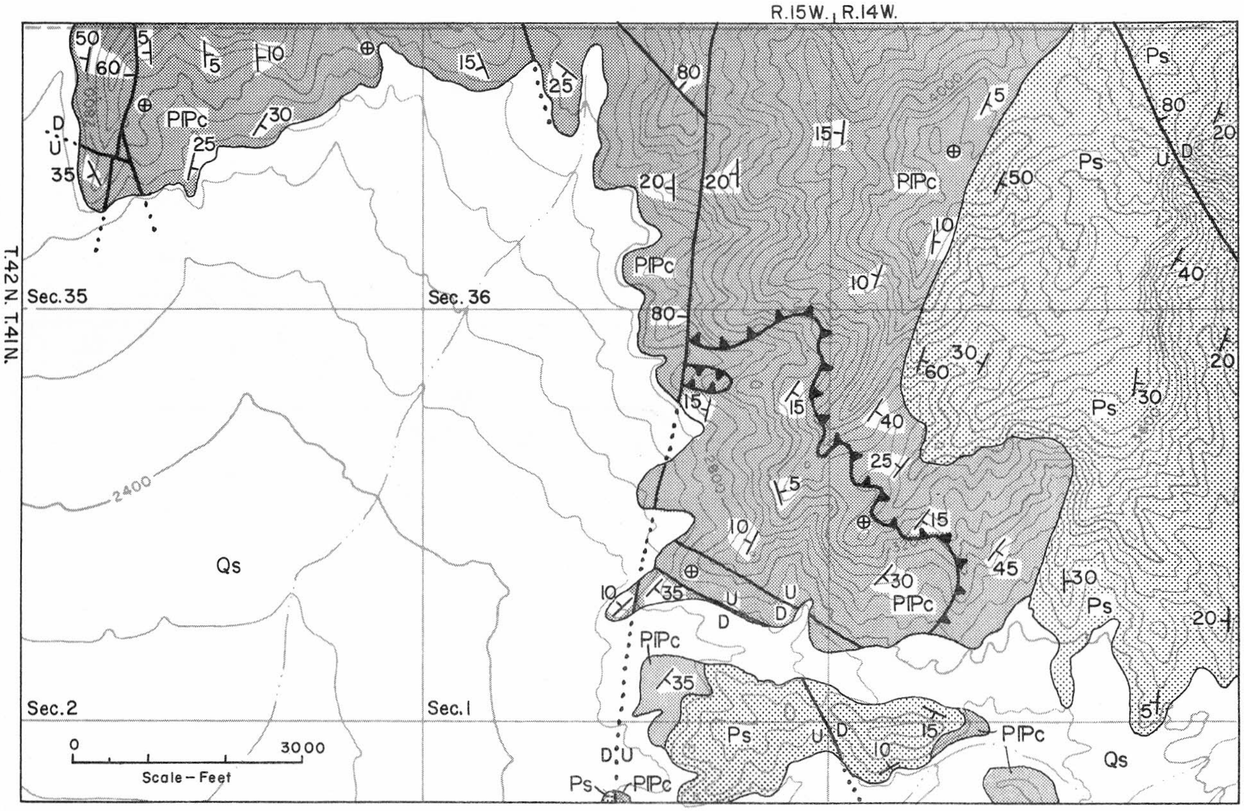


Figure 4. Geologic map of the Beaverdam thrust fault. Qs, alluvium; Ps, Supai Formation; PIPc, Callville Limestone.

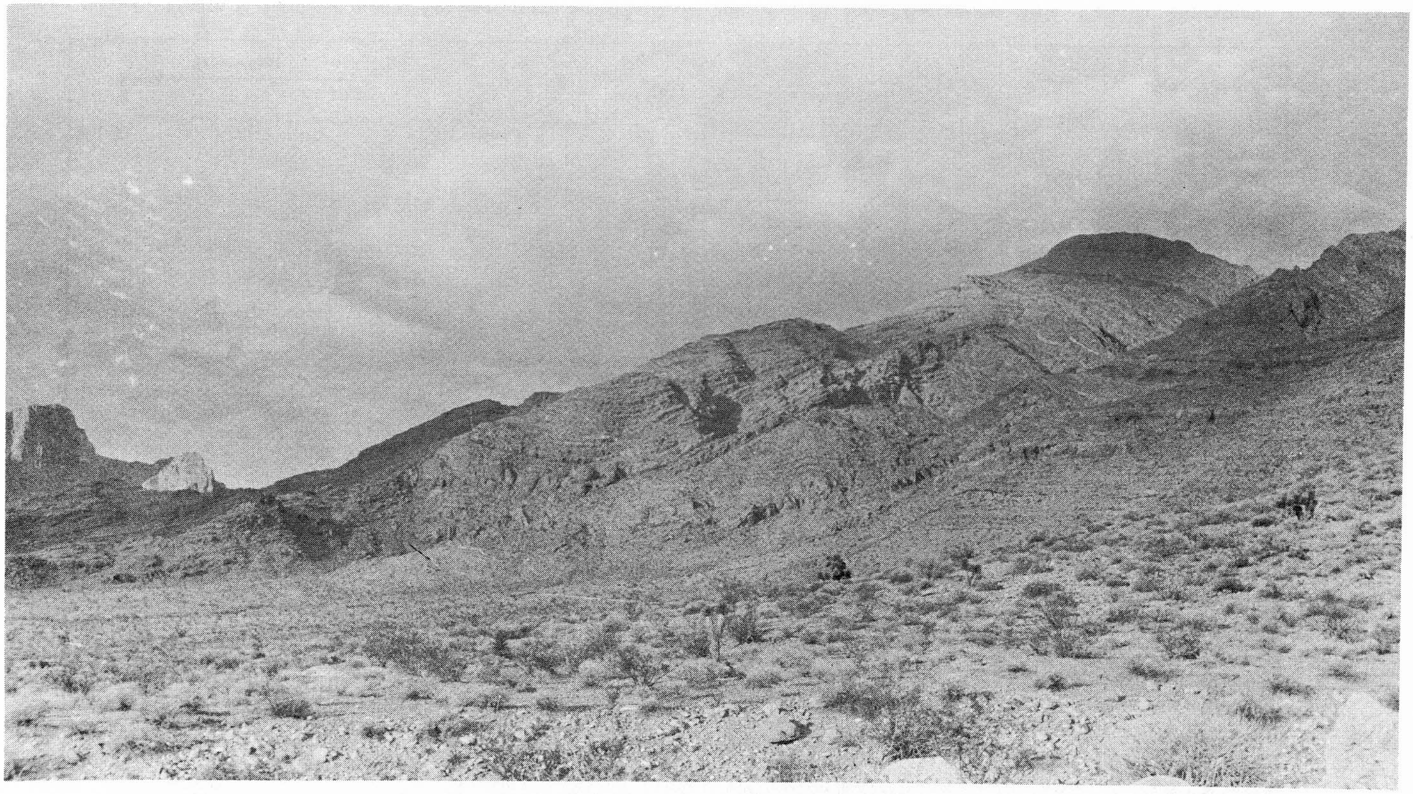
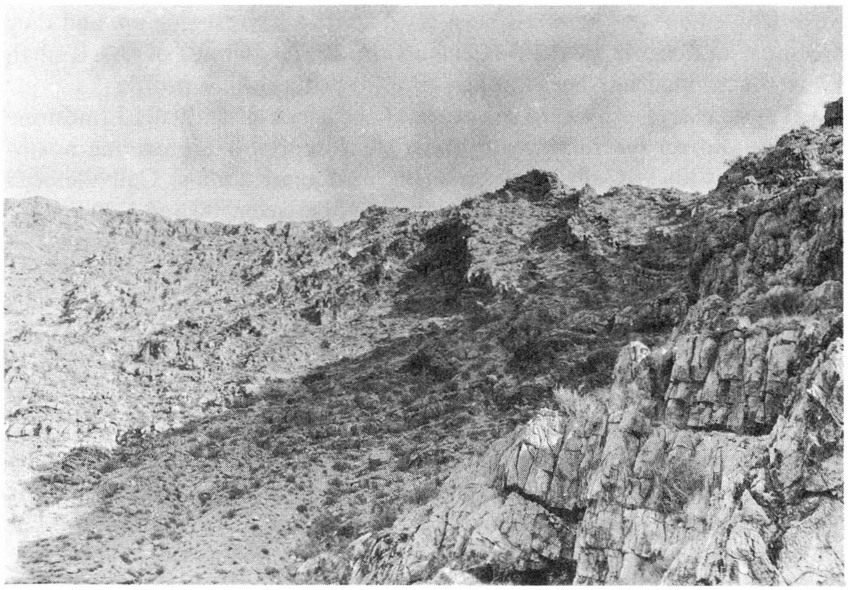


Plate XI. Area of folded Beaverdam thrust fault — location of fault trace is not obvious (see Plate IV for location and orientation of photograph).

A. Truncated and discordant beds of Callville Limestone adjacent to fault plane. View nortnward.



B. Folded and brecciated Callville Limestone in upper plate. View northeastward.

Plate XII. Details of Beaverdam thrust fault (see Plate IV).

Where exposed, the thrust cuts Callville Limestone and the fault plane is nearly parallel to the bedding in the footwall block. Both the limestone and the fault plane are folded. Locally, however, the upper plate is folded more sharply and perceptible angular discordance occurs across the fault.

In many places the fault plane is not easily discernible. As the writer frequently has found it to be the case in other areas where thrust faults cut limestone, considerable recrystallization has taken place, and the break has been largely "healed." However, in such cases, the zone is marked by 50 to 100 feet of highly shattered limestone (see Pl. XIIB) and the fault can be located at least within those limits.

Although the magnitude of the stratigraphic throw is not constant because of the differential folding across the fault plane, lower units of the Callville Limestone have been consistently thrust over upper Callville Limestone and in a westerly direction the fault cuts progressively older beds in the Callville. In places, beds in the lower plate have been tipped up (see Pl. XIIA) in such a manner as to suggest that the upper plate moved east, dragging the lower beds with it.

In the mesa-like block of Kaibab Limestone immediately east of the outcrop of the thrust, a set of closely spaced faults, which are interpreted to be minor imbrications of the Beaverdam thrust, further suggest eastward thrusting. These faults, none of which shows more than 10 to 15 feet of displacement, strike essentially north-south and dip steeply to the west. Movement on them has been reverse, that is, west side up, and they are most noticeable in their effect on the lower contact of the Kaibab Limestone which has been broken into a sawtooth-like profile.

In the extreme western exposure of the block of Callville Limestone cropping out on the Utah state line a steep reverse fault striking north-south brings lower Callville up from the west against upper Callville beds in the eastern block. A stratigraphic throw of between 500 and 1,000 feet is indicated. As shown in structure section A-A' (Pl. II), this fault is also an imbrication of the Beaverdam thrust fault and its attitude is compatible with thrusting from the west.

Differential folding across the plane of the Beaverdam thrust has been noted above and some of the aspects and implications of this feature warrant further consideration.

The evidence cited thus far fairly well establishes that the upper plate of the Beaverdam thrust moved toward the east. How far to the east the fault extends is not known, inasmuch as the leading edge of the fault has not been found in outcrop. However, the relations along the fault and in the rocks to the east suggest that it dies out in the vicinity of Cedar Wash. The fault plane follows quite closely the bedding in the footwall and it is therefore doubtful if any significant folding of the footwall occurred during the thrusting. Indications, are, however, that appreciable folding

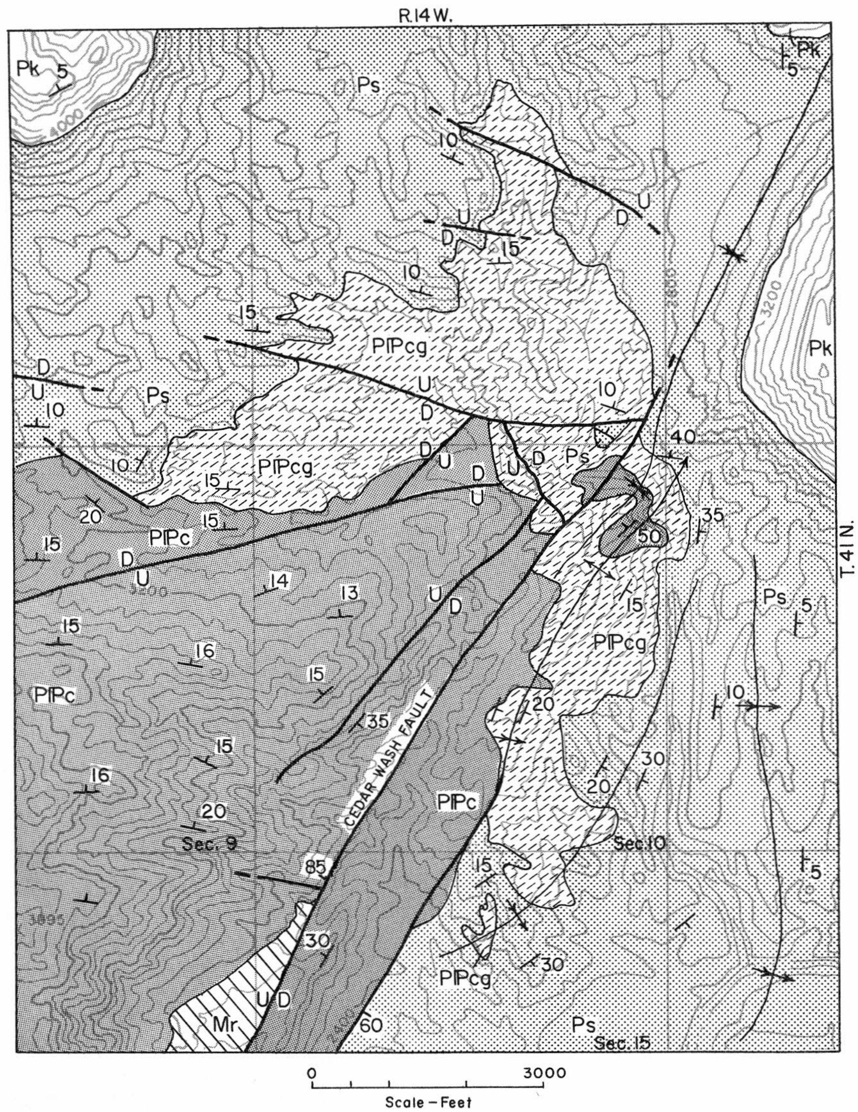
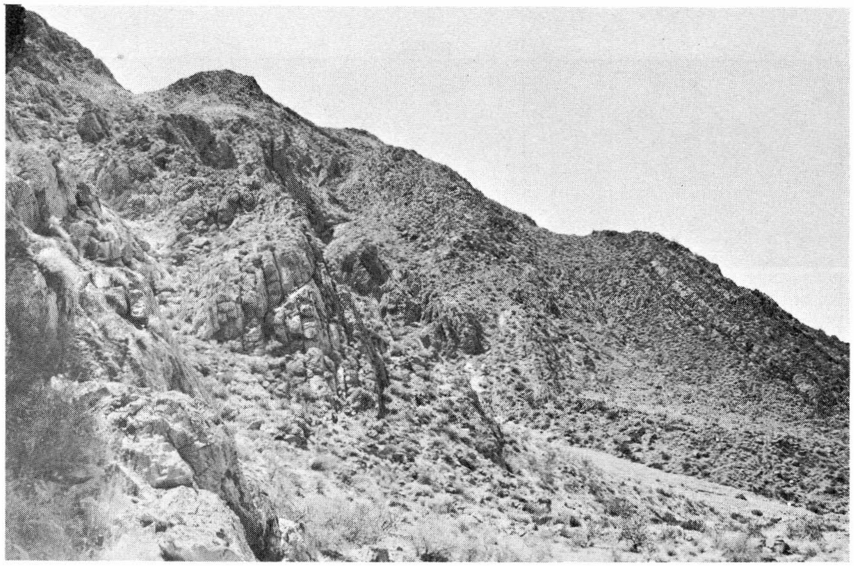


Figure 5. Geologic map of the Cedar Wash area. Pk, Kaibab Limestone; Ps, Supai Formation; PIPc, Callville Limestone; PIPcg, gypsiferous member of Callville Limestone; Mr, Redwall Limestone.

occurred in the hanging wall and it is this folding, or rumpling, in conjunction with the imbricate faulting, that accommodates the displacement toward the east and accounts for the fault dying out in that direction. This folding also accounts for the local discordance in dips observed across the fault.



A. Steeply dipping Redwall and Callville limestone in imbricate plate at west end of Cedar Wash fault.

B. "Flat-irons" formed by imbricate plates at west end of Cedar Wash fault. Trace of Piedmont fault concealed beneath fan debris near base of range.

Plate XIII. West end of Cedar Wash fault (see Plate IV).

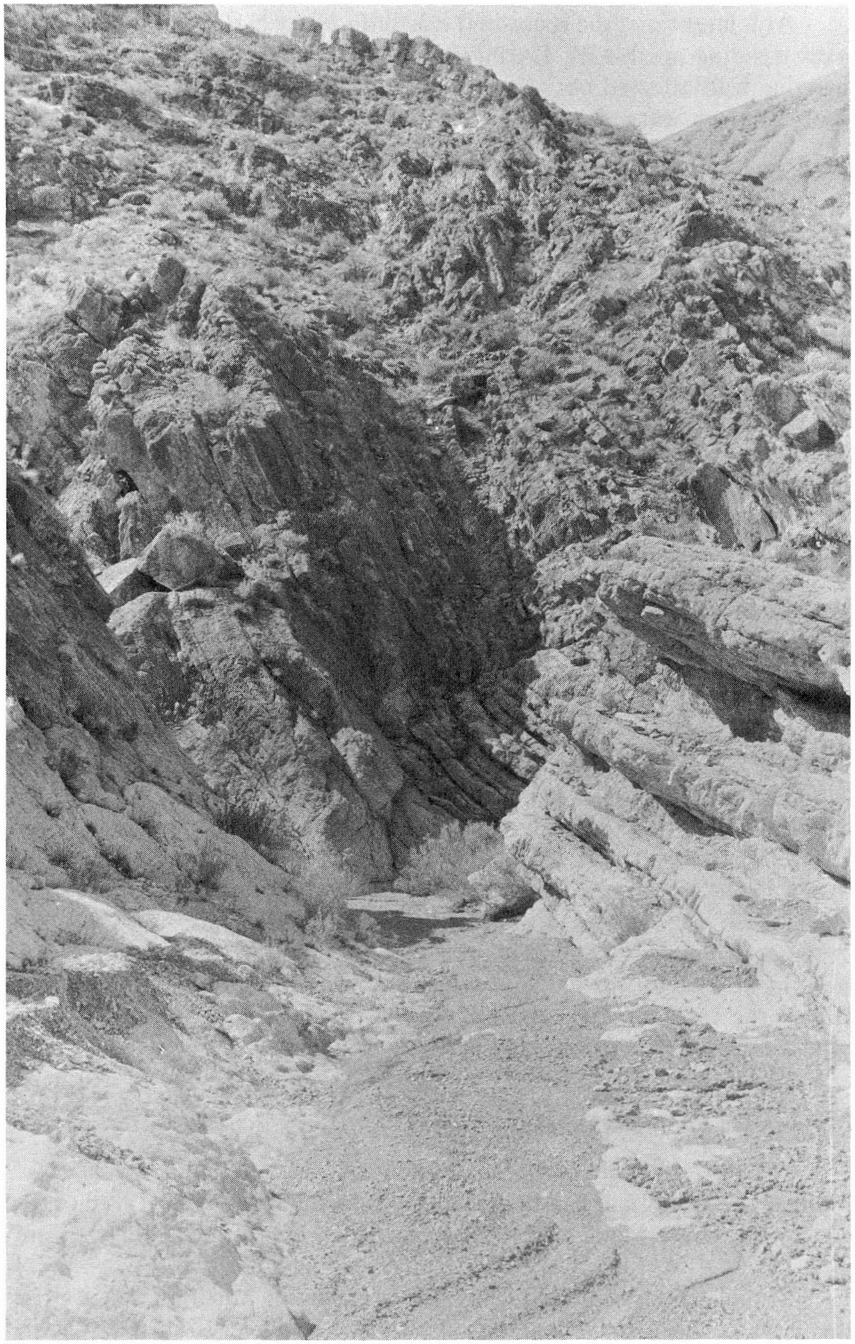


Plate XIV. Folded Callville limestone beds beneath gypsum at north end of Cedar Wash fault. View southwest (see Plate IV).

At a later time, the rocks in the vicinity of the fault were folded along axes trending north-east. During this period of folding, not only was the hanging wall affected but also the plane of the fault and the rocks in the footwall were warped.

Cedar Wash Fault

Cedar Wash is the point of origin of several faults (see Fig. 5), and one of the more important of these is a steep reverse break to which the name Cedar Wash fault has been applied.

Cedar Wash fault extends southwest from the gypsum beds in Cedar Wash, across the Virgin River, to the mouth of Figure 4 Canyon where it apparently terminates against Piedmont fault (see Pl. XIII). As indicated on the structure sections (Pl. II), the dip decreases from vertical in Cedar Wash to about 60°NW. in Figure 4 Canyon. The stratigraphic throw on the fault increases southwestward from zero at its northern end to over 1,000 feet where it is exposed south of the Virgin Narrows.

East of the Virgin Narrows a tear fault, striking N.20°W., intersects Cedar Wash fault. It has affected only the hanging-wall block of Cedar Wash fault and movement on the tear fault is such that the west block has been shifted relatively to the south and up.

The concentration of structural features near Cedar Wash is attributed largely to the gypsiferous unit occurring at the top of the Callville Limestone in that area. Because of its lower yield strength the incompetent gypsum deformed early during the episode of compression and this deformation took the form of folding and squeezing (see Fig. 5). Along the discontinuities thus formed, the more competent limestones first folded (Pl. XIV) and then, with increasing stress, ruptured. The inhomogeneity in strain in the vicinity of the gypsum caused deflections in the local stress field which dictated the attitude assumed by these faults. As the faults lengthened, however, the affect of the gypsum on the stress field lessened and the attitude of the faults at a distance from the gypsum reflects more nearly the regional stress pattern. In the case of Cedar Wash fault, this entailed a decrease in dip southwest along the strike.

Cottonwood Fault and Related Features

Cottonwood fault crops out east of Mount Bangs, at the head of Sullivans Canyon, and can be traced northward along the west wall of the canyon for some 4 or 5 miles. At its northern end it is cut off by Front fault.

At the head of Sullivans Canyon and extending north for 1 or 2 miles the fault is marked by a band of bleached and recrystallized Calville Limestone in the footwall which has been pushed up into steeply east-dipping ridges (see Pls. XV, XVI) by Precambrian and lower Paleozoic rocks in the hanging wall.

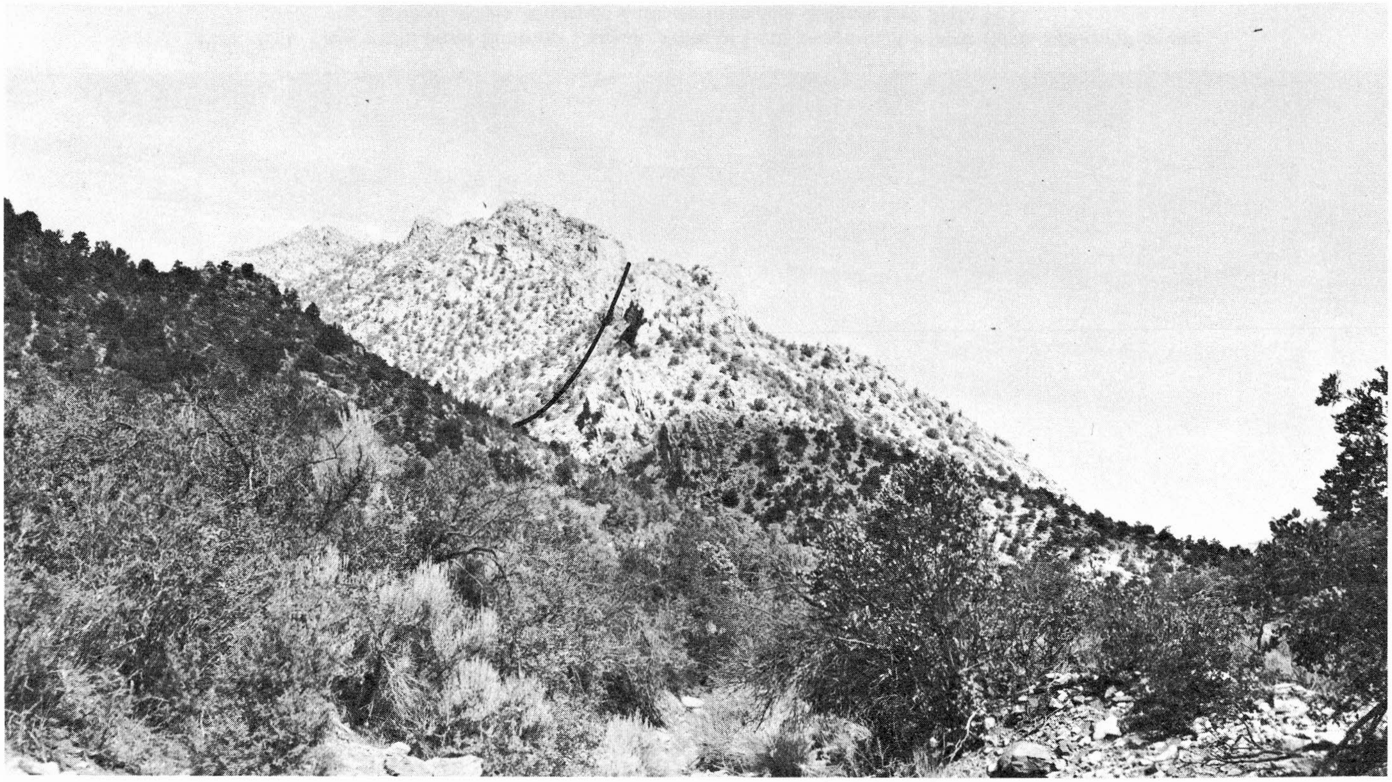


Plate XV. View north along trace of Cottonwood fault. Lower Paleozoic limestones in hanging wall block (left), thrust over units of the Callville in the footwall (right)(see Plate IV).

Plate XVI. View north, down Sullivans Canyon. Trace of Cottonwood fault in near ridge, east-dipping east limb of Virgin Mountain anticline in middle distance (see Plate IV).

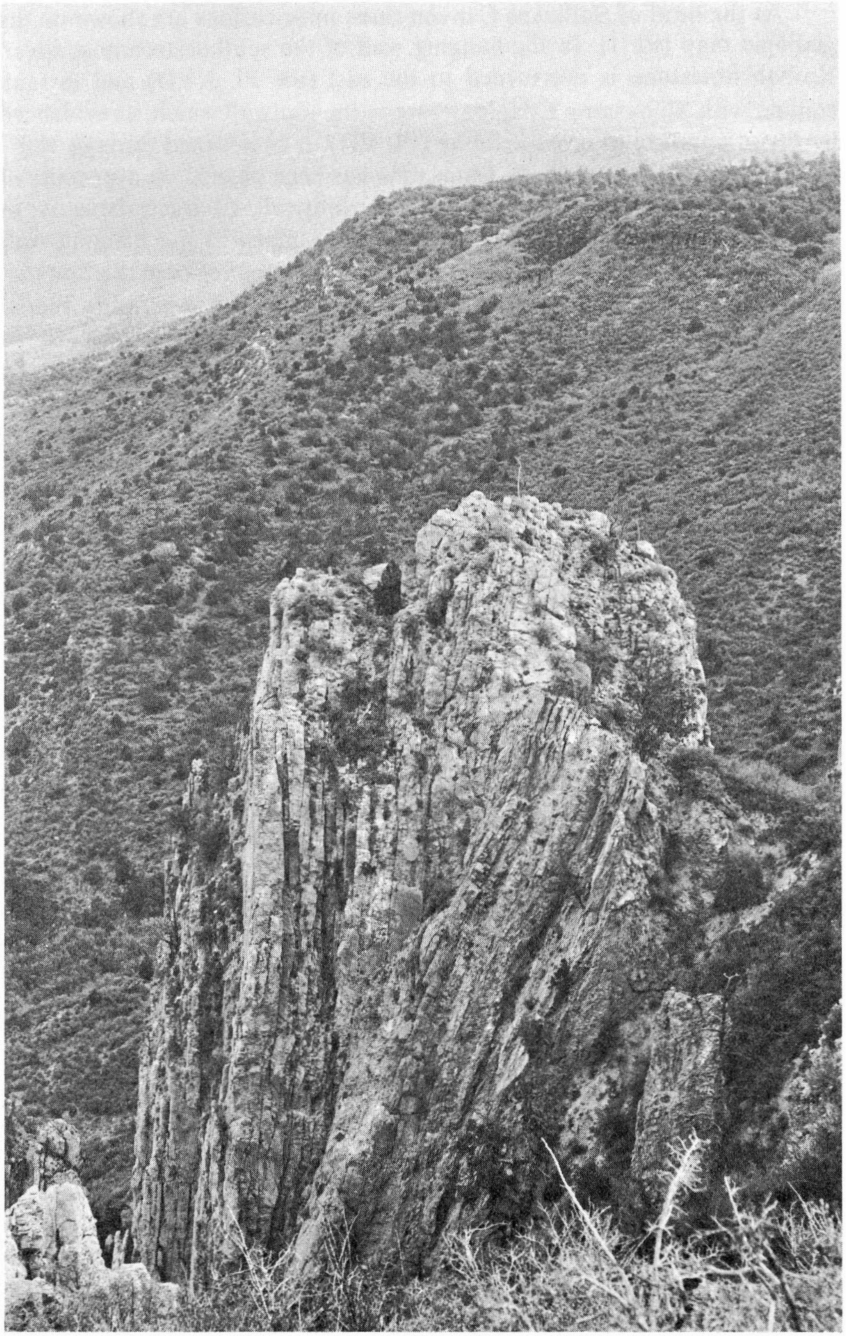


Plate XVII. Overturned Kaibab Limestone in hanging wall of Cottonwood fault. View north; beds are vertical or steeply overturned to west (see Plate IV).

At the head of Sullivans Canyon three imbrications are shown on the geologic map (Pl. I). In the hanging wall of the southeasternmost sliver, Kaibab limestone is overturned to the east (see Pl. XVII) and in fault contact with Shinarump Conglomerate in the footwall which, as evidenced by the orientation of cross-bedding (Pl. VII), is overturned through 180°. In the central sliver, Callville Limestone has been pushed up over units of the Supai Formation which occurs in the footwall. Characteristically, in each sliver, dips steepen down into the fault plane in the hanging wall block as the fault is approached (Pl. XVIII), and the rocks in the footwall block, adjacent to the fault, are dragged up by the overriding block. Evidence of this drag effect can be seen in the rocks exposed between Gates and Mullen Spring and the area of the imbrications. Here, as the fault cuts successively higher units in the stratigraphic column they are turned up very much as though by a plow-share; the resistant units, such as the Kaibab, forming east-dipping ridges and the incompetent units, such as the Moenkopi Formation, accommodating the stress by squeezing and changing thickness.

The upper two imbrications at the head of Sullivans Canyon extend to the south for no more than a mile before they rejoin along a tear fault which strikes N.20°W. South of the tear fault, lower Paleozoic rocks have been thrust over the Pennsylvanian and Permian rocks in the lowermost imbrication and these, in turn, have moved up on the main strand of Cottonwood fault against Triassic and Jurassic rocks. As shown on the geologic map (Pl. I) and the block diagram (Pl. XIX), the lower Paloezoic rocks moved on a spoon-shaped fault surface, the Spoon Fault of Plate I, the outcrop of which curves west to the head of Elbow Canyon, where it is cut off by Front fault.

The mass of lower Paleozoic rocks in the hanging wall block of the spoon-shaped thrust have been brecciated, bleached, and recrystallized, presumably as a result of dynamic effects associated with the faulting. These rocks have also been altered along fractures and a small amount of copper mineralization is associated with the alteration. Although considerable prospecting and development work have been done, no production has been recorded.

South of the spoon thrust, the main strand of Cottonwood fault extends down upper Cottonwood Wash, for which it is named, and into upper Tom and Cull Wash (see Pl. II, sections L-L' through O-O'). Along this segment of the fault exposures are poor; much of its trace is concealed beneath Cenozoic gravels and basalt flows and where it does crop out it is in the soft Moenkopi Formation and exposures are inconclusive.

Its extension to the south is confirmed, however, by the relations between the Shinarump Conglomerate and the Kaibab Limestone. Following the outcrop pattern to the south, the Shinarump Conglomerate crops out at several places with dips varying from near vertical to slightly

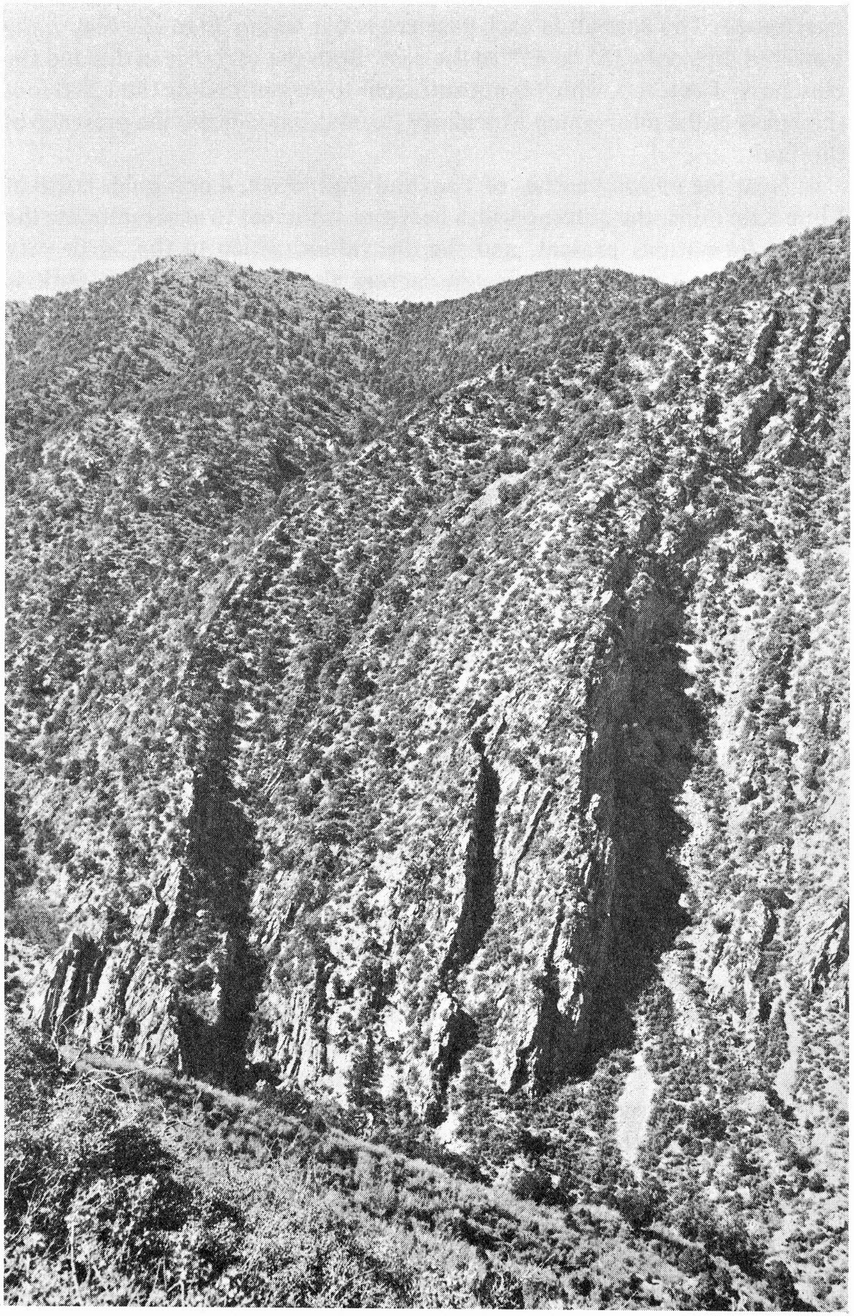


Plate XVIII. View south of Callville Limestone in hanging wall block of Cottonwood fault. Trace of fault concealed behind slope in foreground. Note steepening of dip as fault plane is approached (see Plate IV).

overturned. The Kaibab in each case crops out within 50 to 200 feet to the west and dips only 35° to 45° to the east. Both the variance in dip and the closeness of outcrop, which is not sufficient to accommodate the 1,500 foot thickness of the intervening Moenkopi Formation, indicate the presence of the fault.

Near the middle reaches of Tom and Cull Wash, 4 or 5 miles north of Lime Kiln mine, the outcrop width becomes sufficient to accommodate the several formations present, and the dip values, which to the north vary sharply, are more nearly constant across the formations. The fault is arbitrarily dropped at this point as a surface feature and although still considered a break in the subsurface, in the competent Paleozoic limestones, it is believed that the displacement at the surface is accommodated by folding in the incompetent Moenkopi Formation.

FRONT FAULT

Front fault is one of the longer faults in the Virgin Mountains, measuring some 26 miles in length. Its position in front of the prominent west-facing cliffs northeast of Lime Kiln Canyon suggested the name applied to it. This fault is traceable from Cabin Canyon, in the southwestern part of the area, northeastward to the head of Elbow Canyon and then northward, almost to the Virgin River.

For fully three-quarters of its length Front fault strikes N.45°-50°E., parallel to the trend of the zone of high-angle reverse faulting. At the northeastern end of the reverse fault zone, Front fault deflects to the north. Throughout its entire length it is a high-angle fault at some places dipping east, and at others dipping to the west.

Net displacement is such that Precambrian metamorphic rocks have been upthrown in the western block and are in contact, variously, with Precambrian metamorphic and intrusive rocks and with lower Paleozoic sedimentary rocks. Throughout much of its extent, however, it separates metamorphic rocks from granite. At its northern end, the Paleozoic rocks rest on granite east of the fault and on metamorphic rocks west of the fault. These relations are difficult to explain by any mode of movement compatible with the measurable displacement of the Paleozoic rocks involved. They are easily explained, however, if two periods of displacement are recognized, in which the earlier one occurred prior to the start of deposition of Paleozoic sediments.

Several faults in central and northern Arizona show evidence of Precambrian movement and then post-Paleozoic displacement of an opposite nature; notable of these is the Butte fault, in Grand Canyon (Darton, 1925). On Front fault, also, there is some evidence that this is the case.

The displacement of the Paleozoic rocks at the north end of Front fault shows conclusively that the net post-Paleozoic movement has resulted in the west block moving relatively upward. The Precambrian metamorphic rocks were developed from Older Precambrian sedimentary and volcanic rocks which are presumed to have been metamorphosed during the same orogeny in which the granite was emplaced. This being the case, the metamorphic rocks, would represent the cover into which the granite was intruded, and, therefore, should be structurally higher than the granite. This, however, is not the case across Front fault. The metamorphic rocks and the granite crop out at the same elevation, even after post-Paleozoic movement which, relatively, dropped the granite. From this it is concluded that either the Precambrian movement on Front fault was of opposite sense to that of the post-Paleozoic episode and, in all probability, of much greater magnitude, or that it had an appreciable strike-slip component.

NORMAL FAULTING

Faults in the Virgin Mountains exhibiting normal displacement can be placed into two groups, those which are essentially parallel to the axis of the range and those which are transverse. Of these, the former are by far the more important. At least six show stratigraphic displacements in excess of 1,500 feet and are discussed individually. The transverse faults, on the other hand, which seem to be most abundant in the hanging wall block of the reverse fault zone, are considered as a group.

Grand Wash Fault

Grand Wash fault extends generally north-south along the eastern edge of the mapped area (Pl. I). The outcrop of the fault plane can be traced, almost continuously, to the north into Utah for several miles, and to the south as far as the head of Black Canyon. Farther to the south, the fault is concealed by Cenozoic deposits but its extension in that direction is demonstrated by the scarp forming the Lower Grand Wash Ledge and by the relative positions of the Paleozoic sediments in the ledge and in the tilted fault-blocks to the west. On this basis, it extends for several miles south of the Colorado River and has a total length in excess of 80 miles. Wherever exposed, the fault plane dips to the west and the displacement has been normal, the west block moving down relative to the east block.

The segment of the fault between the Arizona-Utah boundary and Black Rock Mountain is exceptionally straight. It strikes north-south and dips steeply to the west. At the state line (see Pl. II, section A-A') the contact between the Kaibab Limestone and the Supai Formation in the hanging wall block is in juxtaposition with sandstone beds in the footwall block that occur near the middle of the Supai Formation. This indicates a net stratigraphic throw of 600 to 700 feet. However, the rocks in the hanging wall have been considerably affected by drag against the fault and it is possible to account for at least 300 feet of additional displacement, indicating a total stratigraphic throw of nearly 1,000 feet.

Near the Virgin River, the fault dips 70°W. and basal beds of the Kaibab Limestone in the west block have been downthrown against the uppermost units of the Callville Limestone, indicating at least 1,200 feet of stratigraphic throw. Between the river and Black Rock Mountain a branch fault cuts into the east block and can be traced for some 4 miles to the south. This feature strikes slightly east of south and dips about 55°W., into the main Grand Wash fault (Pl. II, sections C-C', D-D'). That it is younger than the main strand of the Grand Wash fault is attested by the fact that it cuts the capping of basalt on Black Rock Mountain, whereas the main branch does not.

Displacement on the branch fault, as on the main fault, is normal. Moderately steep westerly dips developed in the sliver between the two strands strongly suggest drag in the hanging wall of the branch fault and the branch probably represents a local deflection of the Grand Wash fault during a late stage of movement. Total stratigraphic displacement across the two faults measures 1,200 feet, or very nearly the same as the displacement recorded to the north, across the single strand of the Grand Wash fault. This suggests that locally the total displacement on the Grand Wash fault is distributed over more than one plane of rupture.

At Black Rock Mountain, the main strand of the Grand Wash fault passes under the basalt cap and is concealed for a distance of about 5 miles. Where it re-emerges, in Pocum Cove, it separates beds of the Chinle Formation in the hanging wall from shale of the Moenkopi Formation in the footwall. As evidenced from the relations of these formations, the throw is about 900 feet in this area. No clear planes of rupture were observed along the trace of the fault in the rather incompetent rocks cropping out in Pocum Cove and therefore no accurate measurements of its attitude could be made. Its general strike in this area, however, is S.20°E. and it dips steeply to the west.

Four miles northeast of Mud Springs, the Grand Wash fault extends out of the area, to the east. In a short distance, however, it changes strike to S.25°W. and crops out at the east edge of the area, approximately 2 miles east of Sand Spring. Here also the nature of the disrupted rocks, the Moenkopi and Chinle formations, is such that sharp fault planes are not exposed and accurate dip values cannot be obtained. However, the relative straightness of the fault trace in areas of topographic irregularity, indicates a fairly steep angle of dip. Along this segment, Shinarump Conglomerate is in contact with basal Moenkopi beds and about 1,600 feet of throw is indicated.

At the head of Black Canyon, the Grand Wash fault passes under alluvium and does not crop out again to the south in the area of the geologic map (Pl. I).

Near the mouth of Hidden Canyon, basin deposits of Pliocene-Pleistocene(?) age are in depositional contact with the Paleozoic rocks in Grand Wash Cliff and the youngest basalt flows have poured into the present canyon. At no place was evidence seen suggesting that these basalts were cut by the Grand Wash fault. However, remnants of flows are resting on Kaibab Limestone high on the cliffs east of the canyon, and these are believed to be correlative with the older basalts in the Pliocene-Pleistocene(?) pile of gravels and flows at Mud Mountain. From this it is inferred that movement on the Grand Wash fault, in the vicinity of Hidden Canyon, was late Pliocene or early Pleistocene(?) in age.

West Branch Fault

West Branch fault is located east of Mud Springs and between 1 and 2 miles west of the segment of the Grand Wash fault striking S.20°E. It trends approximately S.25°E. from Black Rock Mountain and intersects the S.25°W. segment of the Grand Wash fault at the east edge of the area. Along this fault, as with the Grand Wash fault, the west block is relatively downthrown, and basal Navajo sandstone is in contact with uppermost Moenkopi strata, indicating a stratigraphic displacement of at least 1,500 feet. There is little question that the displacement on this fault accounts for the disparity in the displacements observed on the southeast and southwest trending segments of the Grand Wash fault and it is to this relationship that the name West Branch fault alludes.

At Black Rock Mountain, the West Branch fault passes under the basalt cap, reappearing on the north slopes, between Quaking Asp and Sullivans Springs. These slopes are carved in the soft strata of the Moenkopi and Chinle formations and considerable slumping and sliding has taken place. Consequently, outcrops are obscured and the structural relations cannot be plotted with any degree of certainty. The stratigraphic relations, however, suggest that the West Branch fault continues north, crossing the floor of Sullivans Canyon near Gates and Mullen Spring, and terminating against Front fault, part way up the faulted east flank of the Virgin Mountain anticline.

Whereas the sedimentary rocks to either side of the West Branch fault south of Black Rock Mountain are only slightly tilted, north of the mountain the fault separates beds of markedly different attitudes. East of the fault, the Kaibab Limestone and Moenkopi Formation dip gently to the east. West of the fault, sedimentary rocks of the Callville Limestone, Supai Formation, Kaibab Limestone, and Moenkopi Formation dip moderately to steeply to the southeast and south. To the north, the increased deformation in the rocks of the west block is a reflection of the zone of reverse faulting which apparently did not affect the rocks to the northeast, in the east block of West Branch fault.

Sullivans Canyon Fault

Sullivans Canyon fault can be traced continuously from its intersection with the West Branch fault at Gates and Mullen Spring north to the mouth of Sullivans Canyon, a distance of 9 miles (see Pls. XX, XXI). At its northern end it terminates against the Cedar Wash fault where it has a displacement of only a few tens of feet in which Kaibab strata are faulted against Kaibab strata.

Throughout its length, Sullivans Canyon fault dips steeply to the east and displacement is normal, the east side down-dropped relative to the west side.

As the fault is traced southward up Sullivans Canyon, the stratigraphic throw increases continuously to a point about 5 miles from the mouth of the canyon, west of Lost Spring, where the throw measures about 2,700 feet; upper Supai beds are in contact with medial units of the Redwall Limestone. South of this point the displacement decreases somewhat and at Gates and Mullen Spring it is approximately 2,000 feet.

The variance in stratigraphic displacement along the strike of Sullivans Canyon fault may be partially the result of hinging at the north end. Undoubtedly, however, much of it is the result of differential arching on either side of the fault. Presumably, the arching is a part of the folding that is related to the formation of the Virgin Mountain anticline.

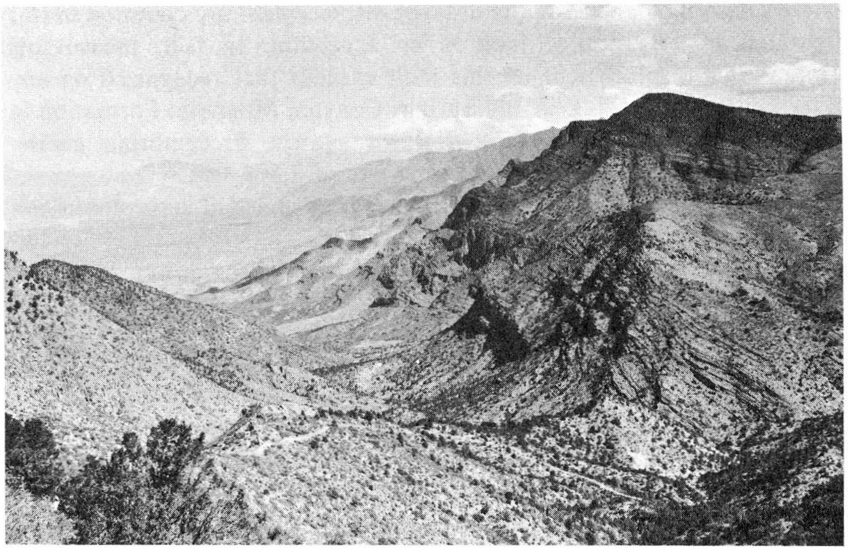
Hungry Valley Fault

Hungry Valley fault, so named because of its location along the west edge of Hungry Valley, is traceable from Whitney Ranch, north along the Arizona-Nevada boundary to Big Springs Canyon, and thence northeast, down Lime Kiln Canyon, (Pl. XXIIA), to its intersection with Front fault. Throughout most of its length, it forms a steeply dipping zone from 100 to 500 feet wide. Where it crosses Lime Kiln Canyon, the fault dips 80°E. and in Hungry Valley the dip is 60°-80°E. In several places slivers of limestone, intermediate in stratigraphic position to the rocks in either wall of the fault, are caught in the zone. These blocks, some of which measure nearly a mile in length and up to 400 feet in width, invariably are strongly brecciated.

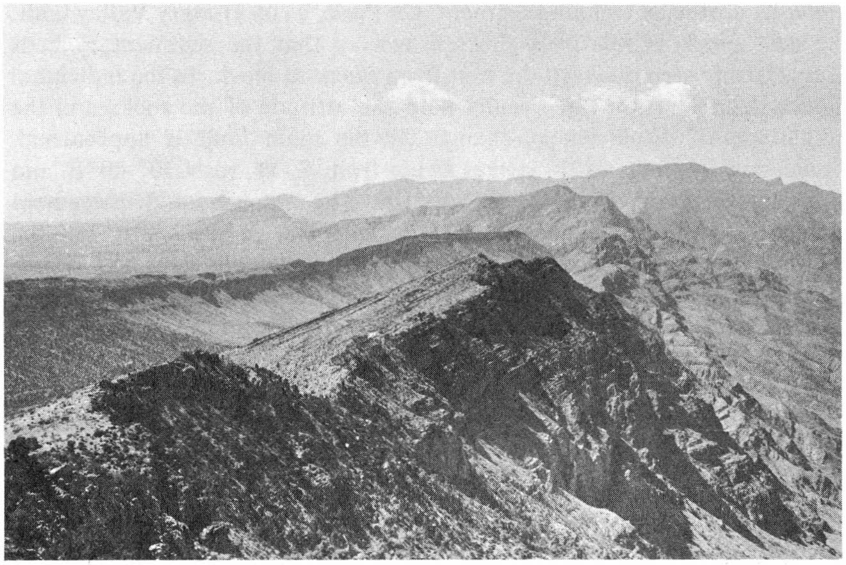
Along its southern part, Hungry Valley fault strikes nearly north and is relatively straight. Between Big Springs Canyon and Lime Kiln Canyon, however, the average strike is N.40°E. and the fault trace is quite sinuous, giving the false impression at places that the dip is much flatter than actually is the case.

Plate XX. View south, up Sullivans Canyon. Brecciated and recrystallized limestone, marking trace of Sullivans Canyon fault, forms wedge-shaped mass on west canyon wall in middle of picture (see Plate IV).

Plate XXI. Sullivans Canyon fault near base of west wall of Sullivans Canyon. Light colored Supai Formation in hanging wall and gray Redwall and Callville limestones in foot wall (see Plate IV).



A. View down Lime Kiln Canyon along trace of Hungry Valley fault. Precambrian rocks to left and Paleozoic on right.



B. View southwest along steep west flank of range. Front fault passes along base of cliff, off picture to right.

Plate XXII. Fault-line scarps of west flank (see Plate IV).

As described above, faults of large displacement are common in this area and Hungry Valley fault is no exception. In fact, measurable stratigraphic displacement on this fault exceeds that recognized on any other fault in the area; near Big Springs Canyon, Moenkipi Formation in the east block has been faulted down against Precambrian gneiss, indicating a normal displacement in excess of 7,500 feet.

Although the Hungry Valley fault has been included in the discussion of normal faults, a case can be made for significant left lateral strike-slip movement. The fracture pattern, as exposed in the lower Paleozoic limestones in the eastern block in Lime Kiln Canyon, consists of two sets, one striking N.40°E. and dipping vertically, essentially parallel to the fault at that point, and a second striking N.20°W. and dipping vertically. This pattern is compatible with compressional forces oriented N.10°E. whereby a strike-slip component of displacement in which the eastern block moved relatively to the northeast could be expected. This is consistent with the relative positions of the lower Paleozoic sediments on either side of the fault; that is, basal Paleozoic rocks at approximately 4,800 feet of elevation in the west block, near Hungry Valley, and also at about the same elevation in the east block, some ten miles to the north.

Several subsidiary faults striking between N.-S. and N.25°W. cut the east block in the vicinity of Hecs Hole and intersect Hungry Valley fault along its northeast trending segment. On these, as on Hungry Valley fault, the east block is relatively downthrown so that the sedimentary beds progressively step down to the east from block to block. In the individual blocks delineated by these faults both the attitude of the rocks and the magnitude of displacement changes as the main fault is approached. Traversing south to north, strikes swing from E.-W. to N.30°-40°E. and dips steepen from 15°S. to 40°-50°SE. The amount of displacement increases to the north and apparently decreases to the south, but the southern ends of these faults are concealed under alluvium. As shown diagramatically in Figure 6, such faults could develop in relief of the drag forces that would be set up in response to left lateral strike slip on the Hungry Valley fault.

Lime Kiln Fault

Lime Kiln fault, which passes just east of Bunkerville Mountain, trends generally north-south, and contains as a fault sliver the block of Kaibab Limestone (see Pl. XXIII) in which the Lime Kiln manganese mine has been developed. At its northern end it veers northeast and intersects Front fault in much the same fashion as does Hungry Valley fault. Also, the displacement on Lime Kiln fault is similar in sense to that on Hungry Valley fault, that is, east side relatively downthrown.

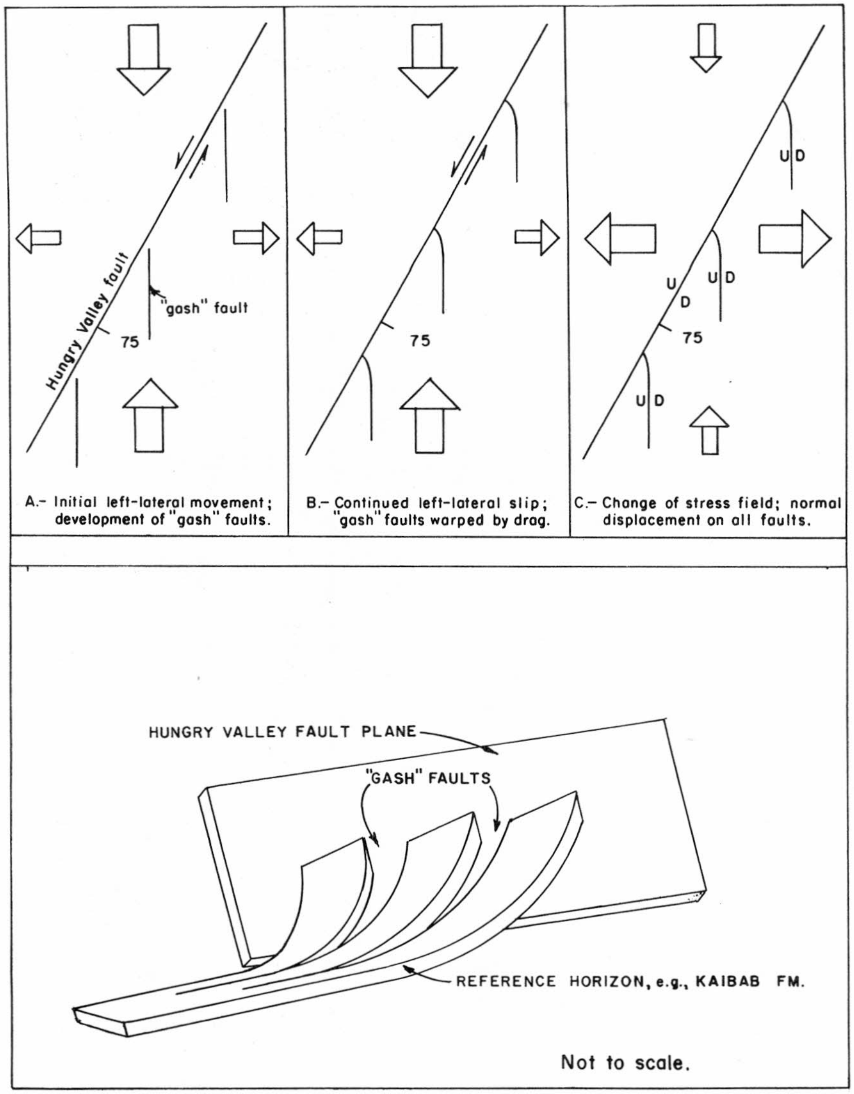


Figure 6. Diagram illustrating possible development of "gash" faults adjacent to Hungry Valley fault.

Near Bunkerville Mountain, Navajo Sandstone in the east block is in contact with Supai Formation in the west block, giving evidence of more than 4,500 feet of stratigraphic displacement.

On the basis of two meager exposures, one near Lime Kiln mine and the other nearly 1 mile south, Lime Kiln fault dips steeply to the east, thus indicating normal displacement. However, along most of its length the actual fault plane is concealed beneath thin slope wash, so it is not certain

Plate XXIII. Sliver of Kaibab Limestone (Pk) in Lime Kiln fault (see Plate IV for location and orientation).

how much of the fault dips east. Near its northern end, where it veers to the northeast, it frays into at least two strands each of which dips steeply northwest and has reverse displacement of about 1,200-1,600 feet. This reverse movement suggests left lateral strike slip along the north trending portion of the fault, in similar fashion to Hungry Valley fault.

Piedmont Fault

The most recent differential movement recognized in the area is along Piedmont fault. This feature, which is traceable along the western base of the Virgin Mountains from the Virgin River south to the vicinity of Lime Kiln Canyon, is marked along much of its length by scarplets cutting the alluvial fans on the piedmont slope.

At the western end of the Virgin River narrows, the fault is precisely at the base of the mountain, and conglomerate of the "Littlefield Formation" (Quaternary?) is in fault contact with Redwall Limestone (Mississippian). Here, the fault dips 65°W. but, although a crushed zone 3 to 4 feet wide involving both the Redwall Limestone and the conglomerate was observed, no physical indication could be obtained as to the relative movement.

Between Hedricks and Lime Kiln Canyons the fault, as marked by the intermittent line of piedmont scarps, offsets Recent gravels in fan deposits, and scarplets as high as 50 feet have been developed. In all cases these scarps face west.

One and one-half miles east of the mouth of Lime Kiln Canyon, two remnants of the very resistant caliche forming the upper member of the "Littlefield Formation," in the Virgin River valley, are perched on Precambrian gneiss fully 400 feet above the head of nearby fans. To the northwest, near the Virgin River, the caliche is overlain by these same fans and it is therefore assumed that the caliche extends southeast, under the fans, to the foot of the mountains where it has been offset by the Piedmont fault. This assumption is believed justified on the basis that the caliche does crop out at the foot of the mountains where Virgin River debouches and can be traced to that point, under fan deposits, from exposures at Littlefield. On the basis of the assumption, and a consideration of the gradients probably developed in the caliche, a crude estimate can be made of the Quaternary displacement of Piedmont fault.

As indicated on the geologic map (Pl. I), the "Littlefield Formation" (QTs) crops out all along the Virgin River, southwest of the mountain front, and floors much of the valley northwest of the river. In nearly all parts of its outcrop area this basin deposit is capped by a nearly uniformly thick layer of the caliche and therefore, in the outcrop area, surface contours can be considered as structural contours on the caliche and can be used to establish gradients. As might be expected for this type of deposit, the Virgin River, where it parallels the mountain front, marks the axis of depression of the caliche. Along this stretch of the river, extending from Littlefield to beyond the Nevada line, the caliche has a gradient of approximately 6 feet per mile. Between Littlefield and the mountain front, the river cuts more nearly normal to the axis of depression and the gradient is about 45 feet per mile. If, then, a gradiant of 50 feet per mile is assumed for the region between the river and the remnants of caliche east of Lime Kiln Canyon, a distance of approximately 7 miles, then the caliche should be at an elevation of approximately 2,200 feet. Actually, the remnants are at an elevation of nearly 3,400 feet, indicating a displacement of 1,200 feet on the Piedmont fault. Here, also, the west side is depressed relative to the east side.

North of the Virgin River the trace of the Piedmont fault is concealed for at least 4 miles. Two miles north of the river, however, evidence of its presence is seen in the outlier of Kaibab and Supai rocks. As shown on structure section D-D' (Pl. II), a normal stratigraphic displacement of nearly 1,400 feet is indicated by the surface exposures and this is in good agreement with the displacement postulated for the fault farther south. Two miles north of the outlier a cave has been formed in the pediment by solution action along the fault. In this exposure the plane of the fault dips 70°W. and sandstone from near the middle of the Supai Formation in the hanging wall block is in contact with basal units of the Callville Formation in the footwall block, indicating a normal stratigraphic displacement of approximately 600 feet.

Transverse Faults

Numerous faults of comparatively minor displacement strike N.30°-60°W. across parts of the Virgin Mountains. These transverse faults are particularly prevalent in the hanging wall blocks of the reverse fault zone. They are not restricted to that block, however, as some occur in the Sand Cove area where several basalt dikes occupy breaks of the same general trend.

By no means have all of the observed faults of this class been shown on the geologic map (Pl. I). To do so would seriously clutter the map. Sufficient examples have been shown, however, to portray accurately their overall effect on the pattern of the range.

STRUCTURAL HISTORY

EARLY STRUCTURAL DEVELOPMENT

Precambrian Events

Information on the Precambrian structural history of the area now occupied by the Virgin and Beaverdam Mountains is meager. The Precambrian rocks in the area attest to sedimentation and at least one period of igneous activity but the details have been largely obliterated by metamorphism. Structural trends in the metamorphosed rocks, such as those delineated by foliation and by the attitude of enclosed pegmatite dikes, are similar to trends developed in rocks as young as Jurassic in age, and, therefore, on the basis of local evidence alone, it is not possible to say with certainty whether these trends reflect both post-Jurassic and Precambrian episodes of deformation or are more nearly characteristic of the Precambrian episode alone. Some light can be shed on this problem, however, by considering a few regional factors.

In central Arizona the Older Precambrian Era closed with an orogeny called the "Mazatzal Revolution" (Wilson, 1939). In a summary of the subject, Wilson (1962, p. 12) concluded that the "Mazatzal Revolution" produced: (1) major folding and foliation which trend prevailingly northeast but locally north, (2) thrust faults and steep reverse faults striking approximately parallel to the folds, (3) strike-slip faults of general north-south and east-west trends, and (4) steep northwesterly faults. The "revolution" culminated with the intrusion of large plutonic bodies of granitic to gabbroic composition. To the north, in the Lower Granite Gorge of Grand Canyon, the foliation of the Older Precambrian metamorphic rocks trends predominantly north-south (Moore, 1925, pp. 163, 164) and in the Virgin Mountains, the foliation trends north-south and northeast-southwest. It is, therefore, concluded that these latter directions reflect the Older Precambrian "revolution" in the Virgin Mountain region.

In Grand Canyon, evidence for a second Precambrian orogeny is contained in the structural relations of the Younger Precambrian Grand Canyon Series (Noble, 1914). This period of structural deformation, commonly called the Grand Canyon Disturbance, marks the last record of Precambrian deformation in that region and resulted in northeast trending folds and faults and northwest trending, tilted, fault-block-mountains which were, apparently, very similar in aspect to the block-faulted ranges characteristic of the modern Basin-and-Range province. Moreover, these structural trends closely parallel those developed during the Older Precambrian "Mazatzal Revolution." However, the Grand Canyon Disturbance was not accompanied by granitic intrusions and did not produce the high-grade metamorphism that is associated with the Older Precambrian "revolution."

Younger Precambrian rocks are not recognized in the Virgin Mountains and there is no proof that they once existed in the area. However, the period of erosion that followed the Grand Canyon Disturbance was of sufficient length and efficacy to reduce the Precambrian surface to a near level plain in the Grand Canyon region (Noble, 1914, p. 61) and easily could have removed all traces of any Younger Precambrian rocks in the Virgin Mountains where, judging from the nature of the unconformity at the base of the Cambrian System, a similar surface was carved prior to the advance of the Cambrian seas. In fact, it did remove completely all topographic evidence of block faulting.

The recognition of faults in the Older Precambrian rocks is difficult. Even those faults that cut the overlying sediments are very difficult to trace very far into the Precambrian rocks. A notable exception, however, is Front fault for which both Precambrian and Cenozoic episodes of displacement are recognized (see pp. 42 and 43).

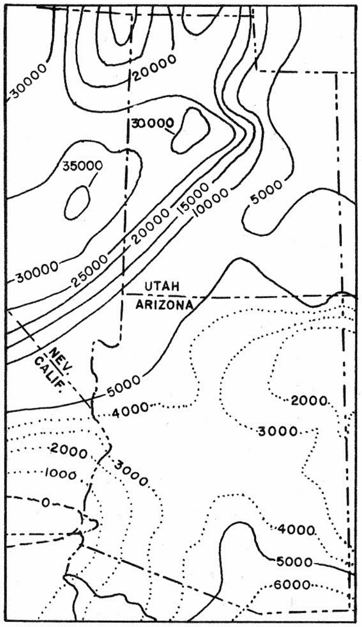
Evidence for dating the ancestral Front fault more closely than merely Precambrian is not conclusive. However, the fact that it cuts granitic rocks that are believed to be related to the latter stages of the Older Precambrian "revolution" suggests that it is younger than that orogeny, and, therefore, probably correlative with the Grand Canyon Disturbance.

Paleozoic Events

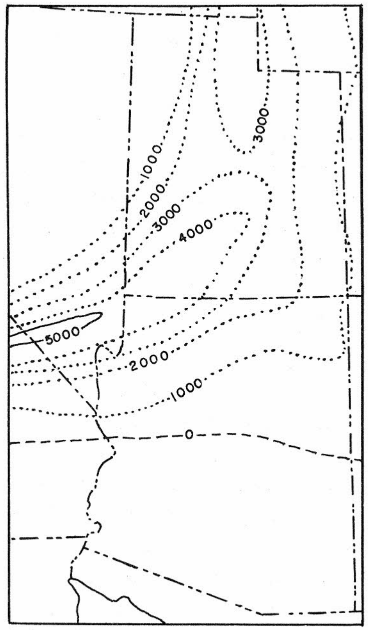
During the Paleozoic Era, the site of the Virgin and Beaverdam Mountains was little disturbed, structurally. The stratigraphic record implies only gentle, epeirogenic subsidence and uplift. By the end of Permian time a net relative subsidence of the Precambrian basement of approximately 7,000 feet had occurred. On a regional scale, however, several factors that had a strong bearing on the later structural history of the range are indicated by trends in Paleozoic sedimentation.

Examination of the isopach map (Fig. 7a) and the cross-section of Paleozoic formations (Pl. XXIV) shows that the Virgin Mountains rose on what had been the edge of a nearly stable shelf extending to the east under the present Plateau province. A short distance to the west, the Cordilleran geosyncline formed a deep trough, suggesting a persistent subsidence in that direction.

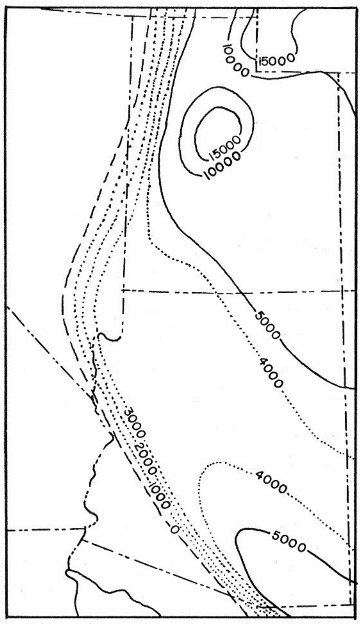
The instability of the Precambrian basement rocks under the deep trough west of the shelf stands in marked contrast to the stability of the



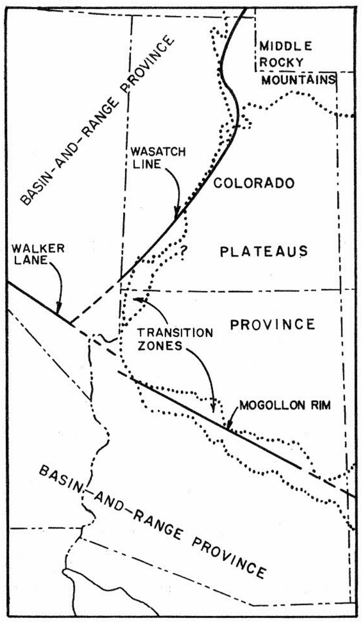
a. Paleozoic isopach map. Modified from Eardley (1963) and McKee (1951).



b. Combined Triassic and lower Jurassic isopach map. After Eardley (1963) and McKee (1951).



c. Upper Cretaceous isopach map. Modified from Reeside (1944).



d. Structural provinces.

Figure 7. Selected isopach maps and sketch showing structural provinces for Arizona, Utah, and parts of California and Nevada.

basement complex upon which Paleozoic rocks were deposited in the shelf area. In the Muddy Mountains, Nevada, only 30 miles west of the Virgin Mountains, the sediments which accumulated from Cambrian through Pennsylvanian time have a thickness of approximately 6,500 feet, as compared with a thickness of 4,400 feet for the correlative strata in the Virgin Mountains. This amounts to an increase of 70 feet per mile between the Virgin and Muddy Mountains. In the northern part of the Spring Mountains, Nevada, 60 miles farther west, nearly 30,000 feet of sediments (Longwell, 1950) accumulated during the same time interval thus indicating a thickening at the rate of nearly 400 feet per mile for the interval between the Muddy Mountains and Spring Mountains. These rates contrast markedly with the average of slightly more than 13 feet per mile from the Virgin Mountains to Little Colorado River, and suggest almost continuous subsidence of the basement in the basin west of the shelf.

The approximate position of the break-in-slope thus evidenced is shown on the isopach map and the structure diagram (Figs. 7a and d). Kay (1951) applied the name "Wasatch line" to the northeastern continuation of this feature in Utah. It was a persistent feature throughout the Paleozoic Era but its fundamental importance is perhaps best illustrated by the fact that it also defines the eastern boundary of the present Basin-and-Range physiographic province and, thus, delimits basically different structural provinces.

MESOZOIC AND CENOZOIC STRUCTURAL DEVELOPMENT

As outlined above, the site of the Virgin and Beaverdam Mountains was essentially a stable area during the Paleozoic Era, although the stage was being set for the major structural events that were to follow.

During Triassic and early Jurassic time a shallow but persistent trough close to the western edge of the old Paleozoic shelf (Fig. 7b) was the site of alternately continental and near-shore marine sedimentation. This trough was supplied with detritus derived largely from positive areas in what is now central Arizona and southern California. In late Jurassic time detritus was being supplied also from the Manhattan geanticline which was rising to the west in what is now central Nevada.

By the end of the Jurassic Period, the uplift associated with the development of the Manhattan geanticline had spread to the east and the eastern trough of the Cordilleran geosyncline ceased to exist as a basin of deposition as far east as the Muddy Mountains, Nevada (Longwell, 1949, p. 965). Uplifts had occurred and clastic sediments were being shed to the east. As deformation continued in the present area of Nevada, by late Cretaceous(?) time the still-stable shelf area in the site of the Virgin

Mountains was receiving debris deposited as the Jacobs Ranch Formation (see Fig. 7c). The essential stability at this portion of the shelf area, at least up through the time of deposition of the basal Jacobs Ranch units, is indicated by the fact that little or no angular discordance exists between that formation and the underlying Navajo Sandstone and that the underlying Paleozoic and Mesozoic formations apparently have not been involved in any periods of major deformation that did not affect the Jacobs Ranch Formation. However, during the deposition of the Jacobs Ranch, the first pulse of the diastrophic movements that ultimately resulted in the molding of the modern Virgin Mountain range took place. In fact, it was probably the easterly migration of the general uplift associated with this series of orogenic pulses that brought to a close the deposition of the Jacobs Ranch and accounts for the angular unconformity between it and the Cottonwood Wash Formation.

The precise sequence of structural events that followed is not known. However, three broad groups of structures can be recognized, on the basis of similarity of trend and/or probable similarity of origin, and the temporal relationships of these groups are easily established (see Table 3). The spatial relationships of the Cenozoic and late Mesozoic structural features of the Virgin and Beaverdam Mountains are shown on the structure diagram (Fig. 3).

The first episode of deformation resulted in the development of the Beaverdam thrust and its related folds and imbricate faults. These structures have been shown in the structural record (p. 36) to pre-date the formation of the northeast-trending folds that warped the Beaverdam thrust plane.

These northeast trending folds, in turn, are associated with the second episode, which produced the Virgin Mountain anticline, Cedar Wash fault, and Cottonwood fault. This episode, without question, was the most severe of the three recognized and was most influential in the building of the present mountain range.

Based on the orientation and nature of the structures included in this group, there is little doubt that they all were produced under essentially the same set of stresses; the northeast trend of the Virgin Mountain anticline and the similar trend of the two steep reverse faults indicate northwesterly compressive forces.

In view of the suspected influence of the gypsum in the Cedar Wash area, it is probable that Cedar Wash fault was initiated early in the second episode and continued to be active throughout this pulse with the development of the tear fault and the northeast folds in the vicinity of Beaverdam thrust. Cottonwood fault, on the other hand, is thought to be a "break thrust" (Billings, 1942, Fig. 149) and probably did not start to develop until the Virgin Mountain anticline had been well established. Once started, however, faulting continued along the Cottonwood zone which became an important locus for the relief of stress, with the resulting

Table 3. Principal Mesozoic and Cenozoic Structural Events.

GROUP	STRUCTURES	DIAGNOSTIC FEATURES	AGE	PRINCIPAL STRAIN
I	Beaverdam thrust and associated folds and imbricate faults.	Faults and fold axes strike north-south; have been affected by later folding.	Post-Jurassic to mid-Cretaceous(?).	East-west shortening
II	Virgin Mountain anticline, Cedar Wash fault, Cottonwood fault, and associated faults and folds. Left lateral(?) component on Hungry Valley and Lime Kiln faults.	Faults and fold axes strike northeast, faults display reverse movement and produced overturned beds. Movement involved Cottonwood Wash Formation but not Muddy Creek Formation.	Late Cretaceous to pre-Middle Miocene; possibly pre-Late Eocene.	Northwest-southeast shortening
III	Grand Wash, Piedmont, West Branch, and Sullivans Canyon faults. Normal displacement on Hungry Valley and Lime Kiln faults.	Large amounts of normal displacement, involve late Cenozoic rocks, produced graben and horst blocks.	Late Pliocene(?) to Recent	Northwest-southeast and east-west extension

development of the several imbricate structures near the head of Sullivans Canyon.

The development of the Virgin Mountain anticline is presumed to have started shortly after the inception of Cedar Wash fault and it probably continued to rise until the major rupturing along Cottonwood fault began. Reconstructing the fold along the line of section R-S (see Pl. III), by removing the displacement on the several faults that roughly parallel the fold axis, a closure of approximately 3,000 feet is obtained at the base of the Paleozoic rocks. After the initiation of movement on Cottonwood fault, it is doubtful if additional, significant folding of the anticline occurred.

Other structures observed in the range may also have been active during this second orogenic episode. The possibility of left lateral strike-slip movement on Hungry Valley fault has been discussed and such movement would be compatible with the northwest compressive forces that must have existed at this time. A similar relation has been suggested for Lime Kiln fault and it also could be explained by a component of movement associated with this episode.

Following the orogenic pulse during which the Virgin Mountain anticline and related features were developed, the newly formed range was subjected to the third structural episode, a period of high-angle normal faulting that has persisted, perhaps intermittently, into Recent time. Relatively large stratigraphic displacements have occurred on several of the faults in this group and a broad graben-and-horst realm has been superimposed on the folded and reverse faulted terrain produced during the previous episodes.

Noteworthy among the faults that were active during this, the third episode in the structural development of the Virgin and Beaverdam Mountains, are the Grand Wash, West Branch, and Piedmont faults.

Other faults, such as Sullivans Canyon, Hungry Valley, and Lime Kiln, also probably were active, to a greater or lesser degree, during this period of deformation but no firm evidence was found by which possible movement on these faults during the second and third episodes could be distinguished.

Front fault was undoubtedly active after the main episode of steep reverse faulting. Cottonwood fault terminates against Front fault at its northern end, as does also the spoon-shaped imbrication, and both must also terminate against Front fault at depth. Such a relationship can be explained in one of two ways: (1) the terminating fault is the younger feature, cutting the terminated fault, or (2) the terminating fault is the older feature, acting as a discontinuity across which the younger, terminated fault, does not break. By their very nature, however, high angle reverse faults, which are products of compression, must have a root-section. In the case of Cottonwood fault this root-section would be to the west and therefore must have been cut off by Front fault.

As described in the section titled "Structural Record," stratigraphic displacements of considerable magnitude occur across the faults of the third episode. It is, therefore, interesting to note that, as shown on the reconstructed portion of section R-S (see Pl. III), there is essentially no net stratigraphic displacement between the footwall of Grand Wash fault and the hanging wall of Piedmont fault. On the other hand, a lateral extension in a nearly east-west direction has occurred, as a result of the normal faulting, and this extension is in excess of 1,200 feet in a distance of 6-1/3 miles.

The majority of the tectonic features in the Virgin and Beaverdam Mountains can readily be placed in order of relative age. Attempts to establish absolute ages, however, are not nearly as satisfactory. Considering the three episodes from youngest to oldest, the period of normal faulting (Group III) is believed to have been restricted almost entirely to late Cenozoic time. The latest period of movement on Grand Wash fault apparently occurred during the interval between the outpouring of the oldest and youngest basalt flows associated with the Pliocene-Pleistocene(?) basin deposits. However, movement has continued into Recent time on at least one fault of this group, as shown by the scarps where alluvial fans are cut by Piedmont fault.

The second group of structures (Group II) involved the Cottonwood Wash Formation but had been essentially completed by Muddy Creek time. On the basis of the stratigraphic correlations established thus far, this places the episode between Late Cretaceous(?) and Miocene(?). Regional relations suggest a pulse of short duration.

In the St. George, Utah, region, Cook (1963) describes the northeast trending Virgin anticline and related minor thrust faults and dates these structures as post-Kaiparowitz (latest Cretaceous) and pre-Claron Formation (Eocene). He considers the orogeny to be Laramide. The validity of the term Laramide need not be considered here, but the similarity of trend, similar form of stress release, and overlap in time of occurrence of these features and those considered in Group II of the Virgin Mountains argue for a close genetic relationship.

Turning to the first group of structural events (Group I), it has been possible to demonstrate only that the Beaverdam thrust and related features are older than the compressional episode that resulted in the Virgin Mountain anticline. Efforts to date the thrust more closely have not proved satisfactory. It is interesting, however, to again speculate briefly on regional relations. Both the Muddy Mountain thrust in Nevada (Longwell, 1949), and the Beaverdam thrust are presumed to have moved eastward under the influence of east-west compressional forces and, further, both bear relatively simple relations to the bedding planes above and below them. Also, both faults developed prior to structures dated as late Cretaceous(?) to mid-Miocene(?) (the Glendale thrust in the Muddy Mountains and the Virgin Mountain anticline in the Virgin Mountains). If then, the Beaverdam thrust can be correlated with the Muddy Mountain thrust, it implies that the site of the Virgin Mountains was at least on the eastern edge of the area involved in the major orogeny which Longwell (1949 p. 465) placed as post-Aztec and pre-Willow Tank. This is equivalent to post-Navajo and pre-Jacobs Ranch in the Virgin Mountains.

PROVINCIAL SETTING

Turning to a consideration of the position of the Virgin and Beaverdam Mountains in the regional structural picture, it will be recalled that the possibility of the range being in a structural transition zone was suggested in an earlier section.

Such a zone was recognized in central and southeastern Arizona, between the Basin-and-Range and Plateau provinces, by Wilson and Moore (1959a, p. 89 and Fig. 12). They formally designated it the "Transition Zone," describing it as a belt within which the strata, although locally folded, tend to be relatively flat. Wilson (1962, p. 96) further described the Transition Zone as being in general more rugged than the Plateau, although lower in altitude, and to be separated from it physiographically by erosional features controlled largely by post-middle Tertiary faulting. In an earlier paper, the writer (Moore, 1958, p. 57) suggested that the area bounded by the Hurricane and Grand Wash faults (see Pl. III) is a structural transition zone between the Plateau and Basin-and-Range provinces. The continuation of this zone into Utah (Fig. 7d) is described in works by Cook (1963) and Stokes and Heylmun (1963).

In Utah, the Transition Zone is characterized by the presence of two well defined trends consisting of: (1) northeasterly aligned faults, folds, and intrusives, and (2) northerly trending normal faults. The extensive thrust faulting common to the Basin-and-Range province is not present in the Transition Zone although minor reverse faults are associated with the northeast trending folds.

Comparing now the structural relations considered indicative of the Transition Zone with those found in the Virgin and Beaverdam Mountains, it is clear that, although the trends in the range are compatible with those ascribed to the Transition Zone, the degree of deformation in the range is greater than that by which the Zone is defined. Therefore, the mountain range proper is placed in the Basin-and-Range province and the boundary between that province and the Transition Zone is drawn along Cedar Wash, Sullivans Canyon, and Cottonwood Canyon (see Pl. III).

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