Geology of the Abajo Mountains Area San Juan County, Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 453

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

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By IRVING J. WITKIND

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A study of a major laccolithic center on the Colorado Plateau

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By Irving J. Witkind

ABSTRACT

The Abajo Mountains area includes about 300 square miles in the central part of San Juan County, southeastern Utah. The mountains, part of the La Sal National Forest, occupy about half the area. The remaining half includes part of the Great Sage Plain to the east and canyon country to the north and south. To the west, a narrow strip of tilted sedimentary strata, known as the Causeway, joins the mountains to Elk Ridge.

The sedimentary rocks exposed in the area range from the Cutler Formation of Permian age to the Mancos Shale of Late Cretaceous age and have a total thickness of about 3,550 feet. These rocks form 16 mappable lithologic units. Surface deposits have been mapped as alluvium, rockslides and boulder fields, dune sand, colluvium, and pediment deposits.

Stocks, laccoliths, dikes, and sills have been intruded into and through the sedimentary rocks. Stocks underlie East and West Mountains, and probably underlie both Shay Mountain and the Johnson Creek dome. Sheathing each stock is a zone of shattered sedimentary rocks intruded by small dikes, sills, and other minor irregular igneous bodies. Through this shatter zone protrude the encircling laccoliths, each attached at its proximal end to the parent stock. Some laccoliths have had their sedimentary cover completely removed and appear as huge masses of igneous rock. Other laccoliths are only partly exposed, and still others are completely buried.

Thirty-one laccoliths have been recognized. Of these, 18 are related to the East Mountain stock, five to the West Mountain stock, two to the Shay Mountain stock(?), and five to the Johnson Creek stock(?). One laccolith is in a graben and cannot be related to any stock. The laccoliths are in only four of the sedimentary units: 18 are in the Morrison Formation, 11 in the Mancos Shale, one in the Chinle Formation, and one in the Cutler Formation. All the sedimentary units, however, have been intruded by smaller igneous bodies. On tenuous evidence, the intrusions are assigned to the Late Cretaceous.

The main igneous rock type in the area is a quartz diorite porphyry that consists of euhedral phenocrysts of andesine, hornblende, and magnetite in a light-gray aphanitic groundmass. All the stocks, laccoliths, dikes, and sills are composed of this porphyry. A quartz diorite porphyry breccia, which surrounds the East and West Mountain stocks, consists of a heterogeneous mixture of quartz diorite porphyry fragments and of blocks of sedimentary rocks; all are embedded in a dark-gray aphanitic matrix. Hornblendite inclusions, in every intrusive body, consist of a tight intergrown mesh of hornblende, plagioclase, magnetite, and small amounts of accessory minerals. These inclusions probably are xenoliths plucked from the basement complex.

Two sets of fractures have been identified. One set antedates the intrusions; the other set was formed as a result of the intrusions. Two grabens that traverse the area were probably established before the mountains were domed. The Shay graben crosses the north flank of the mountains, and the Verdure graben crosses the south flank.

The ore deposits in the Abajo Mountains area are small and of low grade. A few minor uranium-vanadium deposits are in the Salt Wash Member of the Morrison Formation; all have a low uranium content, a vanadium-uranium ratio of about 10:1, and a calcium carbonate content as high as 19 percent. Two types of ore bodies are recognized: oval masses of vanadiferous sandstone averaging 15 by 3 by 10 feet and tabular bodies averaging 40 by 3 by 600 feet. Many small gold and silver mines were operated from 1892 to 1905, but the value of the ore produced never equaled the amount invested. The mines were in mineralized zones near the East and West Mountain stocks and at the contacts between the laccoliths and the surrounding strata.

Three test wells for oil and gas have been drilled in and near the area but all were dry. The area, however, contains suitable structures, and it is underlain by strata that produce oil in adjacent areas. Possible oil and gas traps may be near an ancestral high that was along the west edge of the mapped area.

Water is probably the most valuable natural resource. Perennial streams—North, Indian, Recapture, and Johnson Creeks—provide the water supply for the communities of Monticello and Blanding, Utah.

Other economic resources include road metal (from the pediment deposits) and riprap from the boulder fields formed near denuded laccoliths.

INTRODUCTION

The Abajo Mountains in southeastern Utah are laccolithic mountains, and they closely resemble other laccolithic centers that rise here and there above the Colorado Plateau. These other centers, each containing a core of igneous rocks, include the Henry, La Sal, and Navajo Mountains in Utah; the Ute, Rico, and La Plata Mountains in Colorado; and the Carrizo Mountains in Arizona (fig. 1).

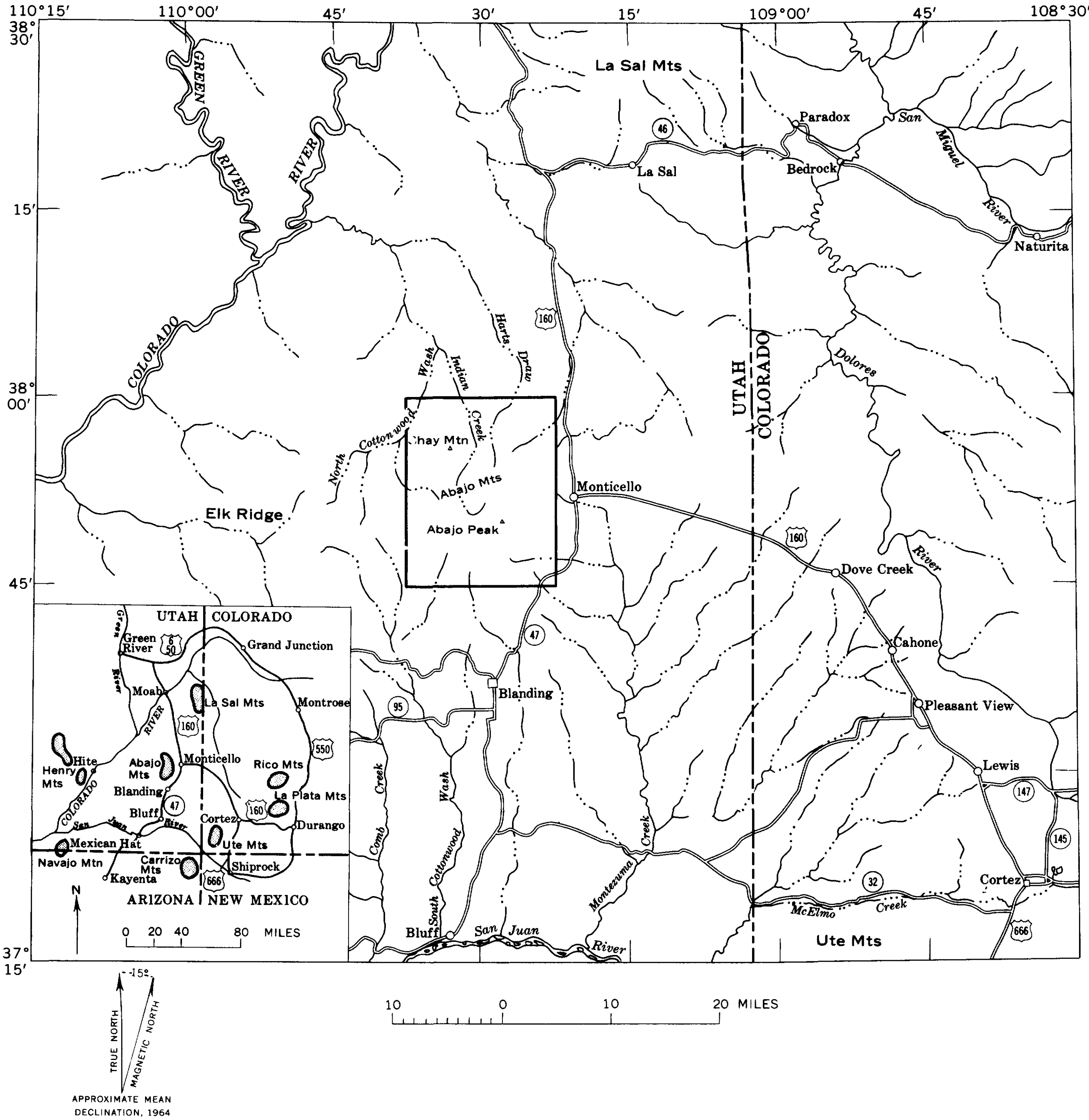


FIGURE 1.—Index map of southeastern Utah and southwestern Colorado showing the Abajo Mountains. Small map shows major laccolithic centers on the Colorado Plateau.

The Henry Mountains have been the subject of intensive geologic investigations. The latest of these studies (Hunt, 1953, p. 148) suggested that the laccolithic centers represent one igneous process arrested at several different stages. Although these isolated mountain groups are similar in structure, igneous rock types, and surrounding sedimentary strata, all differ slightly from one another, the difference presumably reflecting the particular stage at which the formative igneous process was halted. The different laccolithic centers, therefore, can be considered as examples of structural evolution and igneous differentiation. The simple laccolithic mountain is a single dome characterized by a core of igneous rock and small igneous intrusions along its flanks. The intrusions, chiefly diorite porphyry, have little or no mineralized ground near them. Examples are the Carrizo Mountains in Arizona and Shay Mountain in the Abajo Mountains complex. In distinct stages, this simple laccolithic center grades to a more complex one formed by several stocks and their satellite laccoliths. Here, the igneous rocks range from diorite porphyry through monzonite porphyry to syenite. Many mineralized areas are in and near this complex center. Examples are the La Sal Mountains in eastern Utah and the La Plata Mountains in southwestern Colorado.

In 1950, the Geological Survey began a detailed study of the laccolithic centers. Impetus was given to the program by the suggestion that uranium-vanadium deposits may be related to the intrusions (Reinhardt, 1952, p. 9). A report on the Carrizo Mountains by Strobell[1] was completed in 1956, Hunt published a comprehensive report on the La Sal Mountains in 1958, and a report on the Ute Mountains is being prepared, by E. B. Ekren and F. N. Houser. The Abajo or Blue Mountains, as they are sometimes known, form the subject of this report. (See also Witkind, 1958b.)

The work in the Abajo Mountains had a fourfold objective: to relate the area to the intrusive sequence proposed by Hunt (1953), to map the geology, to study the uranium-vanadium deposits, and finally to relate these deposits to the intrusions and to other structural features.

This study was undertaken on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

[1] Strobell, J. D., 1956, Geology of the Carrizo Mountains area, Arizona-New Mexico: Yale Univ. unpublished Ph. D. thesis.

LOCATION

The Abajo Mountains are in San Juan County, southeastern Utah, near the center of the Colorado Plateaus province. About 300 square miles were mapped during the course of this project; the mountains occupy about half of this area and are part of the La Sal National Forest. The adjacent country on the southwest, northwest, and north is typical of the canyon lands of southeastern Utah. To the east, southeast, and south, the Great Sage Plain forms a broad rolling expanse broken by steep-walled canyons. To the west is the forest-covered flat-topped mass of Elk Ridge.

Monticello, Utah, the county seat of San Juan County, is about 2 miles east of the mapped area; in 1957 it had a population of about 3,000. Blanding, Utah, a town of about the same size, is about 9 miles south of the mapped area (fig. 1). Many farms and ranches are east and south of the mountains, and a few are to the north, but to the west the area is still primitive and access is difficult.

TRANSPORTATION

Two all-weather roads curve around the east flank of the mountains. U.S. Highway 160 begins to the north at Crescent Junction, Utah, at its junction with U.S. Highway 6, and extends south through Moab to Monticello (fig. 1). At Monticello it curves to the southeast and passes through Cortez to Durango, Colo. State Highway 47, the other all-weather road, begins at Monticello and extends southward around the southeast flank of the mountains through Blanding, Bluff, and Mexican Hat, Utah, into Monument Valley (fig. 1).

The other roads through the mountains are secondary; most are graded but not graveled. All are impassable in rainy weather, and all are closed by thick snows during the winter months.

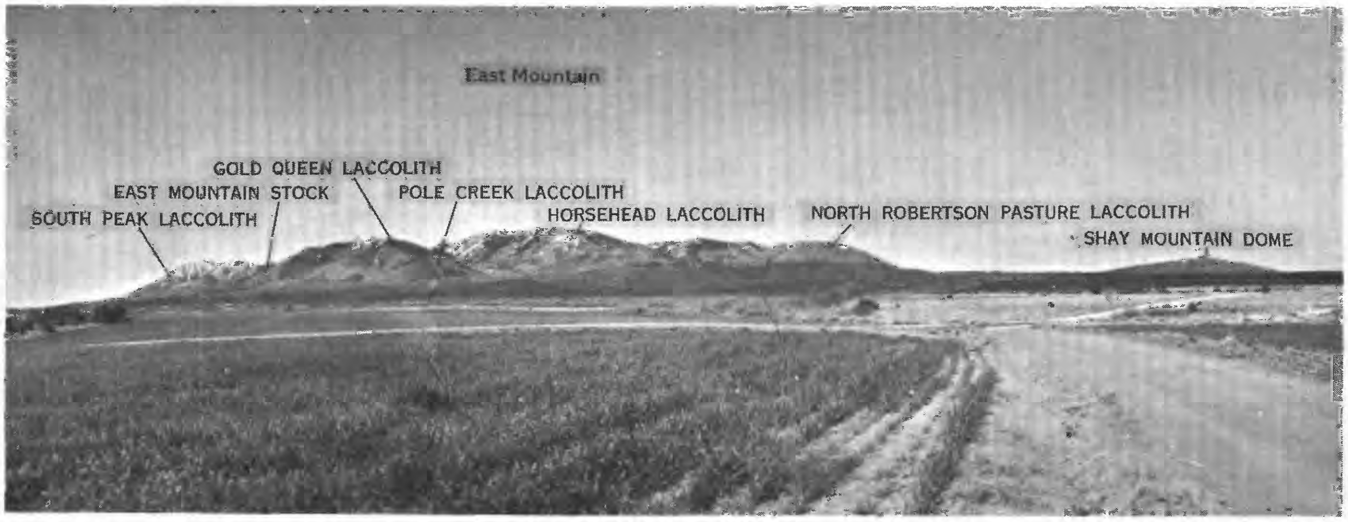
The most serviceable horse trails in and through the mountains are those maintained by the U.S. Forest Service. These commonly serve as trunk trails, from which smaller, less well-defined sheepherder trails lead into the more remote sectors.

GEOGRAPHY AND CLIMATE

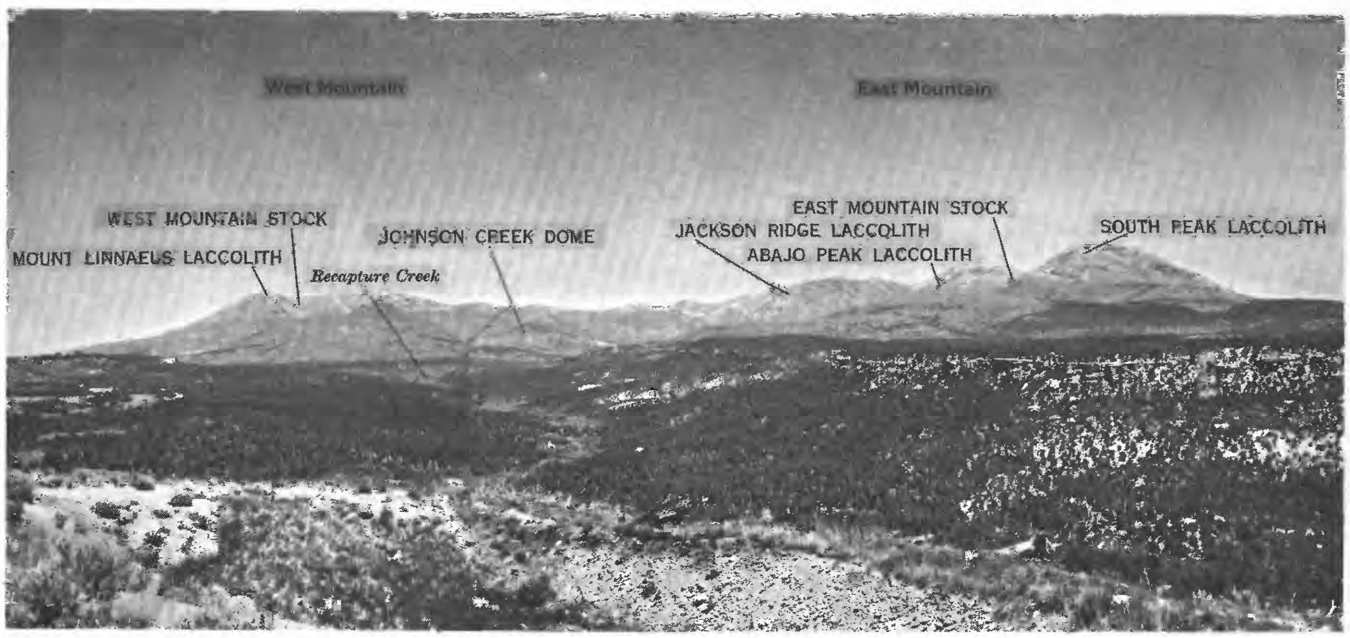
From the east the mountains appear as a low, broad, isolated mass having a slightly undulatory crestline (fig. 2*A*). Rounded peaks with gently sloping sides are common and forests cover the crests. The mountains are about 16 miles long and 10 miles wide; they rise about 5,700 feet above the surrounding terrain. Altitudes range from about 5,800 feet in the northwestern part of the mapped area to about 11,500 feet at the mountain tops.

The Abajo Mountains consist of two unequal parts: a small northern, almost separate mass known as Shay Mountain, and a southern part which contains the main mass of the mountains (pls. 1, 2). The southern part can be further subdivided into West Mountain and an eastern range of hills referred to as East Mountain (fig. 2*B*).

The mountains are ringed by a modified radial drainage pattern (pl. 2). North Cottonwood Creek and its tributaries drain the northwest slopes. Streams in Titus Canyon, Shay Canyon, Harts Draw, and Indian Creek drain the north flanks. All these streams flow northward beyond the mapped area and empty into the Colorado River. Other streams, including Spring, Vega, North, Pole, South, and Verdure Creeks, flow eastward and empty into Montezuma Creek, which then flows southward to the San Juan River, also beyond the mapped area. The south and southwest flanks



A



B

FIGURE 2.—*A*, The Abajo Mountains from the east showing the relations of Shay Mountain on the north to the main mass of the mountains on the south. (Only East Mountain is visible in this view; West Mountain is concealed.) *B*, the Abajo Mountains from the southeast showing the relations of East Mountain to West Mountain. Shay Mountain to the north is not visible.

of the mountains are drained by Recapture and Johnson Creeks and by the streams which flow in Dry Wash, Allen Canyon, and Mule Canyon; all these streams are tributaries of South Cottonwood Creek which also flows to the San Juan River.

Three ecologic zones can be discerned: an Upper Sonoran zone at the base of the mountains, a Transition zone around the lower flanks, and a Boreal zone in the highest parts of the mountains. The Upper Sonoran zone is characterized by broad sagebrush flats, alkali plains, and abundant piñon pine and juniper. Near the upper reaches of this zone, scrub oak and low spreading shrubs appear. The Transition zone represents the change from Upper Sonoran to Boreal and is marked by open grass-covered valleys. Trees such as aspen, willow, maple, alder, and cottonwood and bushes such as elderberry and serviceberry are common. The Boreal zone has a moist cool climate and supports coniferous forests of spruce, balsam fir, limber and foxtail pine, and Engelmann spruce. Many of the mountain meadows in the Boreal zone have a cover of bunch-grass.

The Abajo Mountains area has long warm summers and short winters. Snowfall is light in the Upper Sonoran zone, but is heavy and long-lasting in the Boreal zone. Desertlike conditions prevail in the canyons along the north edge of the area. Near the mountains, however, the climate changes, and upslope it grades into moist humid conditions. These climatic conditions determine the use of the land: The desertlike areas are used chiefly for grazing small herds of cattle. To the east and south, the Great Sage Plain is planted to wheat and pinto beans. In the higher parts of the mountains, some lumbering is done. Many grassy areas in the mountains are used for grazing cattle and sheep during the spring and summer.

In general, good weather prevails and, clear or partly cloudy days far exceed cloudy days (table 1).

PREVIOUS WORK

Little geologic work was done in the laccolithic centers during the early exploration on the Colorado Plateau, and in the middle of the 19th century they were still considered "peculiar mountains" (Peale, 1877). Only upon the completion of a study of the Henry Mountains was it established conclusively that sedimentary strata had been intruded and deformed by igneous rocks (Gilbert, 1880). The intrusive nature of these mountain groups was suggested, however, as early as 1876 by Newberry who stated (p. 99), in referring to the Abajo Mountains, "* * * we found the sedimentary strata rising onto the trachyte core as though it had been pushed up through them."

During 1875 and 1876, while Gilbert was studying the Henry Mountains, W. H. Holmes and A. C. Peale, members of a Hayden Expedition, completed hurried recon-

TABLE 1.—*Climatic summary, by month, Abajo Mountains area*

[Compiled from "Climatic summary of the United States from establishment of stations to 1930, inclusive, section 21," and "Climatic summary of the United States—Supplement for 1931 through 1952," U.S. Weather Bureau]

Recording Station	Time of record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Mean total precipitation (in inches)														
Blanding	Prior to 1931	1.48	1.44	1.28	0.97	0.80	0.45	1.39	1.56	1.25	1.15	1.40	1.74	15.31
	1931–52	1.18	1.20	1.06	.89	.67	.59	.81	1.08	1.44	1.25	.75	1.35	12.27
Monticello	Prior to 1931	1.60	1.79	1.97	1.26	.85	.76	2.14	1.86	1.45	2.59	1.25	1.34	18.86
	1931–52	1.18	.96	1.07	.95	.75	.71	1.35	1.82	1.66	1.64	.77	1.20	14.06
Mean snowfall (in inches)														
Blanding	Prior to 1931	10.4	9.2	4.5	1.5	0.4	0.0	0.0	0.0	0.0	0.5	2.7	11.1	40.3
	1931–52	9.2	5.3	4.1	1.2	.2	Tr.	.0	.0	.0	.3	2.4	12.3	35.0
Monticello	Prior to 1931	14.2	16.5	11.1	3.2	.9	Tr.	.0	.0	.0	.1	5.6	13.5	65.1
	1931–52	19.4	13.1	11.3	4.1	.4	.0	Tr.	.0	Tr.	1.0	4.9	16.6	70.8
Mean temperature (° F)														
Blanding	Prior to 1931	26.6	32.6	39.6	47.6	55.5	66.0	71.3	69.4	61.5	51.3	40.1	28.8	49.2
	1931–52	26.4	31.9	39.0	48.2	56.5	65.2	72.7	71.0	63.2	51.4	37.2	29.7	49.4
Monticello	Prior to 1931	23.2	27.7	34.3	43.9	51.5	61.0	66.2	64.8	57.6	47.6	36.5	25.6	45.0
	1931–52	25.1	29.0	35.4	45.2	53.5	62.0	69.1	67.0	60.3	49.7	36.3	28.5	46.8

Average number of clear, partly cloudy, and cloudy days

[No data available for Monticello]

	Type of day	*Length of record (years)*													
Blanding	Clear	23	14	12	15	12	13	17	9	12	16	18	15	14	167
	Partly cloudy	23	8	8	9	10	12	10	16	13	9	8	8	8	119
	Cloudy	23	9	8	7	8	6	3	6	6	5	5	7	9	79

naissance trips to other isolated mountain groups. Peale visited the La Sal, and Holmes, along with other members of the expedition, visited the Abajo Mountains. Unfortunately, an unexpected snowstorm limited Holmes' stay in the Abajo Mountains to a single day. He climbed Abajo Peak and, although much of the area was covered by snow, noted the intrusive character of the mountains. He (1878, p. 191–192) described the Abajo Mountains as follows:

> * * * The Sierra Abajo consist of a number of small groups of volcanic summits. The trachyte of which they are formed seems to have reached its present place through a number of channels, although probably from the same nucleus. The masses now exposed were doubtless forced up through narrow crevices or apertures until the yielding formations of the Middle Cretaceous were reached, where the melted material spread out to the right and left in great masses and sheets.
>
> All along the east and south bases of the mountains the sandstones of the Dakota group are turned up at high angles.

Holmes inferred that the upturned edges of the sandstones were the result of igneous intrusion.

Peale (1877, p. 561), as a result of his work, concluded:

> The trachyte resting on the sedimentaries lies on the Lower Cretaceous, and probably represents a portion of a mass that was pushed from the nucleus to the sides and forced between the strata.

Gilbert's report on the Henry Mountains (1880, p. 19) established the laccolithic concept in these words:

> The lava of the Henry Mountains behaved differently. Instead of rising through all the beds of the earth's crust, it stopped at a lower horizon, insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds. In this chamber it congealed, forming a massive body of trap. For this body the name of laccolite * * * will be used.

Subsequently the name "laccolite" was altered to "laccolith."

The igneous rocks in all the laccolithic mountains are remarkably alike, and from the first it was assumed that the intrusions were nearly contemporaneous, had been intruded at about the same geologic horizon, and had formed under similar conditions. Hayden (1877) in his cross sections of the Abajo, Ute (El Late), and Carrizo Mountains showed them all as laccolithic mountains similar in structure and rock type.

The first detailed geologic study of the Abajo Mountains was completed during the summer and fall of 1915 by Thorpe who considered them "* * * laccoliths with associated sheets and dikes * * *" (1919, p. 379). More detailed statements by Thorpe (1938a, b) were included in Gregory's (1938) comprehensive review of the San Juan country. Pertinent data of Thorpe's study were also summarized by Butler (1920, p. 618).

During the fall of 1944, a field party of the Union Mines Development Corp., contractors of the Manhattan District, completed a reconnaissance survey of the Abajo Mountains. This work, although carried out hurriedly and under adverse weather conditions, resulted in an accurate and detailed map. The work had two principal objectives: to locate and delineate the Morrison Formation, and to find and examine uranium-vanadium outcrops. The 1944 study was fruitful, for most of the uraniferous deposits known in 1957 were located originally by this party (p. 85).

PRESENT INVESTIGATION

A study of the Abajo Mountains was begun in 1950 by J. D. Sears of the Geological Survey. Sears spent the field season of that year mapping and studying the sedimentary strata that crop out along the east flank of the mountains, but after one season the project was cancelled.

In 1954 the project was reactivated and I was assigned to complete the study. Geologic fieldwork began in June 1954 and was completed in 1957.

All the geologic mapping, except for some detailed mapping, near mines and mineralized prospects, was plotted on aerial photographs. The central and east parts of the area are covered by aerial photographs on a scale of 1:20,000, taken in 1950. The west edge is covered by aerial photographs on a scale of 1:37,400, taken in 1953. In a few parts coverage is incomplete.

Preliminary advance topographic sheets of the west half of the area became available in 1955. Consequently two geologic maps were prepared. The first map was on a planimetric base, and its northeast corner was issued as a Mineral Investigations Field Studies map (Witkind, 1958a). The second map was on a topographic base. The geologic contacts were traced onto transparent plastic topographic base maps by the use of Multiplex and Kelsh plotters (pl. 1).

Almost all the area is mantled by thick colluvium that supports dense foliage. Wherever possible the various geologic units were followed on the ground, but many are so concealed that their exact location and attitude could only be surmised. Consequently most of the geologic contacts on the map are represented by dashed lines. In order to show clearly the bedrock geology and the relations of the intrusions to the adjacent sedimentary strata, many colluvial areas were not mapped; however, in a few places, notably along Indian Creek and Harts Draw, the colluvial cover was so thick that it seemed to warrant mapping as a separate geologic unit (pl. 1).

ACKNOWLEDGMENTS

H. T. Cantor, in 1954, helped in the detailed mine mapping and basic-resource appraisal. P. C. Griffin, during the 1955 field season, helped map most of Shay Mountain and the adjacent terrain. D. R. Tuttle, in 1956, acted as horse wrangler and field assistant during the mapping of the east and southeast parts of the area. G. L. Marshall assisted during the 1957 field season, when the southwest and west parts of the area were mapped.

Marvin Lyman, of Blanding, Utah, identified many of the old mines in the field and spent some time relating the history of the Camp Jackson area. Additional details about some of the mines on the east slope of the mountains were given by Fletcher Bronson and his wife. Mrs. Nora Jones, of Monticello, Utah, supplied information about the early history of several other mines.

I was directed to many of the mountain trails by John W. Redd, Sr., of Monticello, and by Lyman and Dwayne Bayles, of Blanding, Utah. Their instructions greatly facilitated the work.

Appreciation should also be expressed for the aid given by the Forest Rangers of the U.S. Forest Service. J. D. Thomas, ranger at the Baker Ranger Station near Monticello, supplied maps of the area, at times acted as guide, and often suggested feasible routes into relatively inaccessible parts of the mountains. After Mr. Thomas was transferred in 1957, G. LeGrande Olson, who replaced him, helped in all possible ways.

STRATIGRAPHY

About 3,550 feet of sedimentary rocks is exposed in and around the Abajo Mountains. These strata are of Permian, Triassic, Jurassic, and Cretaceous age and comprise 16 mappable lithologic units (table 2).

Overlying these strata are surficial deposits that have been mapped as five separate units: alluvium, rockslides and boulder fields, dune sand, colluvium, and pediment deposits.

CONCEALED FORMATIONS

Test wells drilled on the west, south, and east sides of the Abajo Mountains have penetrated strata of Permian, Pennsylvanian, Mississippian, Devonian, and Cambrian ages (fig. 3). Each well found the same or correlative units and, by extrapolation, it seems reasonable to expect comparable strata in the Abajo Mountains area. The thicknesses of the units penetrated, however, differ markedly; consequently, in the following tabular summary average thicknesses are used. This table suggests that in the Abajo Mountains area about 5,350 feet of strata, representing five systems, underlies the Organ Rock Tongue of the Cutler Formation.

Generalized summary of formations penetrated in four test wells (fig. 3).

	Thickness (feet)
Cedar Mesa Sandstone Member of the Cutler (Permian)	1,100
Rico Formation (Pennsylvanian and Permian?)	450
Upper part of Hermosa Formation (Pennsylvanian)	1,000
Paradox Member of Hermosa Formation (Pennsylvanian)	1,200
Lower part of Hermosa Formation (Pennsylvanian)	200
Leadville(?) Limestone (Mississippian)	500
Ouray Limestone and Elbert Formation (Devonian)	300
Ophir Formation and Tintic Quartzite (Cambrian)	600
Total	5,350

Most of these concealed strata consist of limestone and dolomite beds that contain thin lenses of shale and sandstone. This sequence is interrupted by the Rico Formation, a fine- to coarse-grained sandstone and the Paradox Member of the Hermosa Formation, largely gypsum and salt. Limestone and dolomite beds, dominant in the upper part of the Cambrian, grade into coarse-grained feldspathic rocks near the base. Most of these basal strata probably were derived from the underlying Precambrian basement complex by erosion.

PERMIAN SYSTEM

CUTLER FORMATION

In the Abajo Mountains area, the Cutler Formation consists of two members: the Cedar Mesa Sandstone Member conformably overlain by the Organ Rock Tongue. The Organ Rock, the oldest unit exposed, is formed by reddish-brown, very fine-grained sandstone, shaly siltstone, and sandy shale. The Cedar Mesa, not exposed in the mapped area, appears to the west in the Elk Ridge area as a massive crossbedded fine- to medium-grained sandstone.

The Cutler Formation consists of detritus shed during erosion of the Precambrian rocks of western Colorado. Near its source, the Cutler consists of coarse arkose and cannot be subdivided, but to the west and south it is finer grained and has been divided into four (or five) members and tongues (Baker and Reeside, 1929, p. 1446; Stewart, 1959, p. 1854). Thus, in the Monument Valley area, the Cutler Formation is divided into four units (fig. 4) which, in ascending order, are the Halgaito Tongue, the Cedar Mesa Sandstone Member, the Organ Rock Tongue, and the De Chelly Sandstone Member.

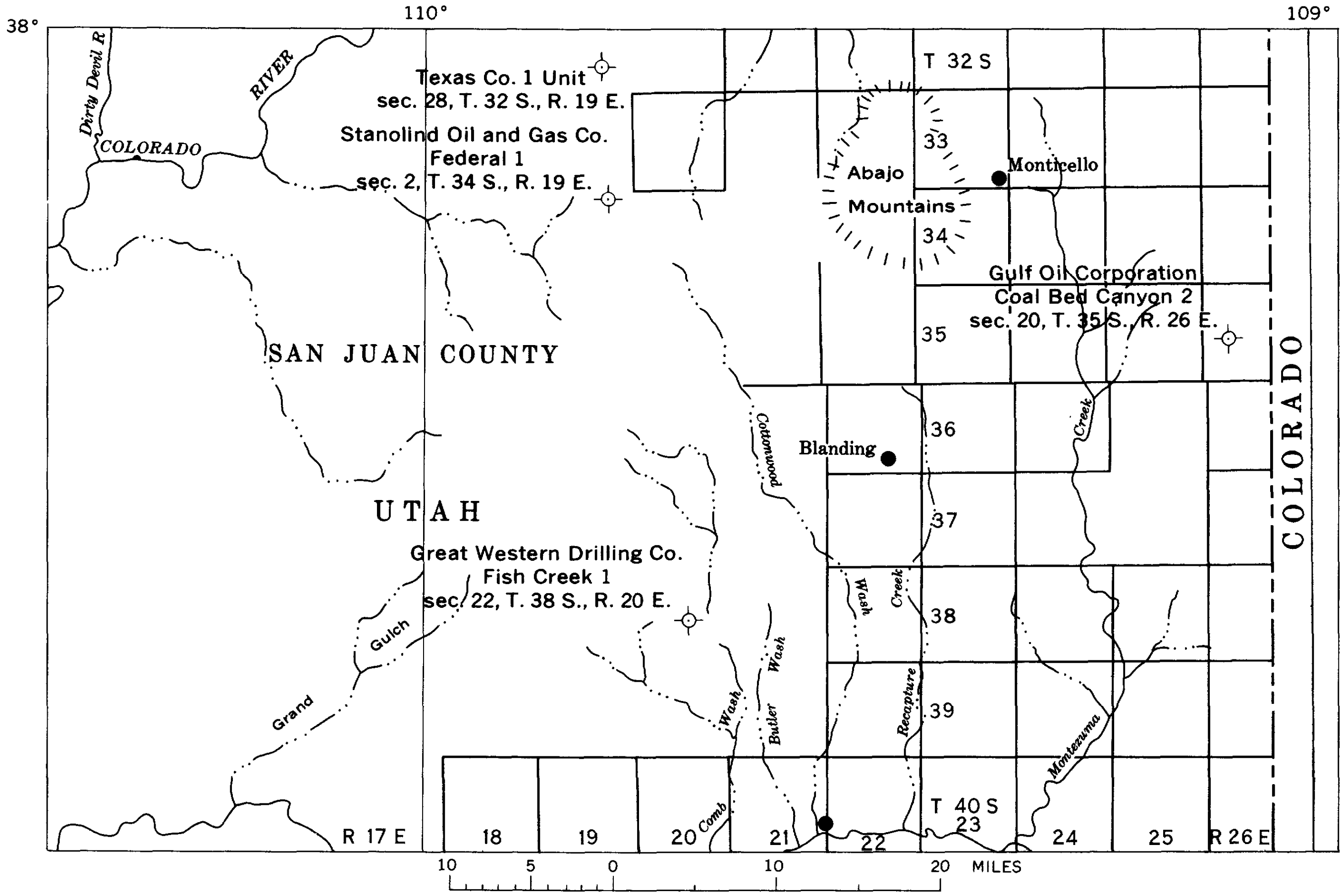
TABLE 2.—*Generalized section of sedimentary rocks exposed in the Abajo Mountains area*

[Total thickness of consolidated sedimentary strata, 3,550 ft]

System	Series	Unit			Thickness (feet)	Lithology
Quaternary		Alluvium			1–40	Dark-brown unconsolidated, poorly sorted mixture of clay, silt, sand, and gravel along streams.
		Dune sand			1–10	Reddish-brown to light-brown unconsolidated deposits of wind-worked fine- to coarse-grained sand.
		Colluvium			1–50	Unconsolidated to partly consolidated unsorted mixture of clay, silt, sand, gravel, cobbles, and boulders forming widespread irregular-shaped masses.
		Rockslide and boulder-field deposits			15	Locally includes rockslides and rock glaciers. Composed of angular boulders of igneous rock.
		Pediment deposits			1–100	Light-gray unconsolidated, poorly sorted deposits of angular to well rounded sand, gravel, cobbles, and boulders of igneous and sedimentary rocks that form broad flaring aprons around the base of the mountains.
		Unconformity				
Cretaceous	Upper Cretaceous	Mancos Shale			700(?)	Dark-gray to black fissile even-bedded shale containing fossiliferous sandy limestone in lowermost strata. Thickness is unknown.
	Lower Cretaceous	Dakota Sandstone and Burro Canyon Formation			30–50 50–75	Light-brown to brown massive to crossbedded conglomerate, conglomeratic sandstone, and sandstone, all tightly cemented. Locally contains green claystone lenses at base and dark-gray carbonaceous seams at top. Commonly entire unit stands as a cliff.
		Unconformity(?)				
Jurassic	Upper Jurassic	Morrison Formation	Brushy Basin Member		275–350	Composed chiefly of light-gray to greenish-gray discontinuous interfingering beds of mudstone, claystone, and siltstone. Locally contains sandstone and conglomerate lenses.
			Salt Wash Member		250–550	Consists of discontinuous light-brown massive to crossbedded sandstone beds alternating with light-gray mudstone and claystone beds.
		San Rafael Group	Summerville Formation		65–125	Reddish-brown even-bedded, slightly fissile siltstone, and local intercalated yellow-brown massive crossbedded fine-grained sandstone. White layer of chert nodules marks upper contact.
			Entrada Sandstone	Moab Sandstone Member	45–50	Very pale orange massive crossbedded, very fine grained sandstone showing traces of bedding planes.
				Lower unit	120	Very pale orange massive to crossbedded friable fine- to medium-grained sandstone that commonly stands as a near-vertical cliff; in places forms hummocky knobs.

TABLE 2.—*Generalized section of sedimentary rocks exposed in the Abajo Mountains area*—Continued

System	Series	Unit		Thickness (feet)	Lithology
Jurassic–Con.	Upper Jurassic—Con. Middle Jurassic	San Rafael Group—Con.	Carmel Formation	35–120	Consists of four units. At the base is a light-brown even-bedded fine- to medium-grained sandstone about 5 feet thick that truncates the underlying crossbedded Navajo Sandstone. Above this unit is a reddish-brown even- to crossbedded fine-grained sandstone about 10 ft thick that locally becomes a shaly siltstone (the "lower red" unit). The third unit is a very pale orange crossbedded fine-grained sandstone about 40 ft thick. The uppermost unit is a moderate reddish-orange even-bedded shaly siltstone about 50 ft thick that locally becomes a fine-grained sandstone (the "upper red" unit).
			—Unconformity—		
Jurassic–Con. / Triassic(?)		Glen Canyon Group	Navajo Sandstone	410	Very pale orange to light-brown massive to crossbedded sandstone that commonly stands as cliff. Locally forms hummocky knobs.
Triassic(?)	Upper Triassic(?)	Glen Canyon Group	Kayenta Formation	185	Pale red massive to crossbedded interfingering sandstone and conglomerate lenses; locally contains a few thin red shale beds.
Triassic	Upper Triassic	Glen Canyon Group	Wingate Sandstone	240	Very pale orange to light-brown massive crossbedded sandstone that weathers to vertical cliffs.
Triassic	Upper Triassic	Chinle Formation	Upper unnamed member	400–570	Basal part consists of reddish-brown shaly siltstone interbedded with dark-gray massive crossbedded platy sandstone. Major part of unit consists of light-gray, pale-red, and orange to reddish-brown mudstone.
Triassic	Upper Triassic	Chinle Formation	Moss Back Member	50–100	Dark-gray massive crossbedded conglomerate and conglomeratic sandstone beds alternating at irregular intervals with light-gray to tan platy medium- to coarse-grained sandstone beds. Unit commonly forms cliffs.
Triassic	Upper Triassic	Chinle Formation	Lower unnamed member	10–180	Pale-red and white mottled shaly siltstone; commonly forms scree-covered slopes.
Triassic	Upper Triassic	Chinle Formation	Shinarump Member	0–20	Yellowish-gray massive crossbedded fine- to medium-grained sandstone containing thin lenses of conglomerate near base.
			—Unconformity—		
Triassic	Middle(?) and Lower Triassic	Moenkopi Formation	Upper unit	210	Dark-brown fissile siltstone and shale intercalated with reddish-brown ripple-marked sandstone.
Triassic(?)		Moenkopi Formation	Hoskinnini Member	50	
Permian		Cutler Formation	Organ Rock Tongue	250	Pale reddish-brown to reddish-brown massive even- to crossbedded fine-grained sandstone and shaly siltstone. Locally contains a coarse-grained arkosic sandstone marked by many angular to rounded fragments and pebbles of brown siltstone.



System	Well name, location, and abbreviated log San Juan County, Utah							
	Texas Co. 1 Unit sec. 28, T. 32 S., R. 19 E.		Stanolind Oil and Gas Co. Federal 1 sec. 2, T. 34 S., R. 19 E.		Great Western Drilling Co. Fish Creek 1 sec. 22, T. 38 S., R. 20 E.		Gulf Oil Corporation Coal Bed Canyon 2 sec. 20, T. 35 S., R. 26 E.	
	Formation	Thickness (feet)	Formation	Thickness (feet)	Formation	Thickness (feet)	Formation	Thickness (feet)
Cretaceous							Burro Canyon Formation	60
Jurassic							Morrison Formation Summerville Formation Entrada Sandstone Carmel Formation	695 50 110 55
Triassic ?							Navajo Sandstone Kayenta Formation	450 135
Triassic							Wingate Sandstone Chinle Formation	230 733
Triassic ?							Moenkopi Formation	
Permian			Rico Formation	210			Cutler Formation	1779
Pennsylvanian	Hermosa Formation Paradox Member	1085 1043	Hermosa Formation Paradox Member Molas Formation	796 1258 28	Upper part of Hermosa Formation Paradox Member Lower part of Hermosa Formation	1075 540 433	Upper part of Hermosa Formation Paradox Member Lower part of Hermosa Formation	1152 1675 151
Mississippian		604	Leadville and Madison	581		362	Leadville Limestone	303
Devonian		320	Ouray Limestone Elbert Formation	49 268		647	Ouray Limestone Elbert Formation	98 480
Cambrian		1040		38		583	Ophir Formation Tintic Quartzite	28 38
Total depth	4944 feet		4218 feet		4840 feet		8442 feet	

FIGURE 3.—Concealed formations penetrated in four test wells. The pre-Permian stratigraphic sequence noted in the log of each well indicates that these or similar strata underlie most of the Abajo Mountains area.

As the Cutler Formation is traced northward, two of its members pinch out—the De Chelly near Monitor Butte in southern Utah, and the Halgaito Tongue in the southeastern part of the Elk Ridge area, probably between Arch Canyon and Fish Creek (Lewis and Campbell, 1964) (fig. 4). In the Abajo Mountains and Elk Ridge area, the fourfold division of the Cutler has been reduced to two; the Cedar Mesa Sandstone Member and the Organ Rock Tongue. Still farther north and east the lithologic differences between these two units disappear and the Cutler is mapped as an undivided unit (Baker, 1933).

ORGAN ROCK TONGUE

The Organ Rock Tongue of the Cutler Formation is exposed both along the walls of North Cottonwood Creek and in the center of a huge dissected dome near the south flank of the mountains which I refer to as the Johnson Creek dome (pl. 1).

The Organ Rock Tongue consists of an irregular sequence of beds of reddish-brown (10*R* 4/3)[2] very fine grained sandstone, shaly siltstone, and sandy shale. These beds weather to form steep-sided slopes more or less concealed by scree, talus, and a dense cover of scrub oak.

About 20 feet below the top of the Organ Rock is a pale-red (5*R* 6/2) coarse-grained arkosic sandstone which generally forms a prominent ledge. Thin lenses of small angular fragments and rounded pebbles of light-gray, brown, and purple siltstone are near the base of this arkosic sandstone. Most of the pebbles are oval and measure about three-fourths inch on their long axis and one-half inch on their short axis. A few are as much as 2 inches by 1¼ inches. This arkosic sandstone is about 50 feet thick and is both overlain and underlain by the reddish-brown strata of the characteristic Organ Rock.

Because of its limited exposure, this arkosic sandstone could not be traced laterally. It probably is continuous in the mapped area, and is tentatively correlated with one of the many parts of the Organ Rock which extend southward.

The Organ Rock Tongue ranges in thickness from 170 to 270 feet in the Elk Ridge area to the west (Lewis and Campbell, 1964), and is estimated to be about 250 feet thick in the Abajo Mountains area.

The contact with the overlying Hoskinnini Member of the Moenkopi Formation is gradational and is concealed by talus in most places. To the west in the Elk Ridge area the contact is marked by a persistent zone 2 to 3 feet thick of gray to greenish-gray, very fine grained sandstone and sandy siltstone (Lewis and Campbell, 1964). This zone probably extends across the Abajo Mountains area.

TRIASSIC(?) AND TRIASSIC SYSTEM

MOENKOPI FORMATION

Two units make up the Moenkopi Formation in the Abajo Mountains area: a basal unit known as the Hoskinnini Member, and an upper unnamed unit.

HOSKINNINI MEMBER

The Hoskinnini Member of Triassic(?) age consists of beds of reddish-brown (10*R* 4/3), fairly even bedded, very fine grained sandstone and shaly siltstone, which contrast with the dark brown (10*R* 3/3) of the overlying upper unit but are difficult to distinguish from underlying Organ Rock strata. Commonly the Hoskinnini forms a steep scree-covered slope that is continuous with the slopes formed on both the overlying and underlying units.

The Hoskinnini is about 50 feet thick in the Abajo Mountains area, and as much as 100 feet thick to the west in the Elk Ridge area (Lewis and Campbell, 1964).

The contact with the overlying upper unit of the Moenkopi Formation appears conformable, and it is difficult to select any specific bed as the contact. At the lower contact, the change from the reddish-brown of the Cutler to the dark brown of the Moenkopi assists in mapping the units. An angular unconformity may exist between the Hoskinnini and the upper unit of the Moenkopi in parts of the Moab district (Baker, 1933, p. 33). No evidence of such an unconformity was found in the Abajo Mountains area, although an unconformity is in part of the White Canyon area, Utah, and in the western part of the Elk Ridge area (Lewis and Campbell, 1964).

UPPER UNIT

The upper unit of Early and Middle(?) Triassic age is exposed along the valley walls of North Cottonwood Creek and near the center of the Johnson Creek dome (pl. 1). In both localities the unit consists of beds of dark-brown (10*R* 3/3) to reddish-brown (10*R* 3/4) thin to very thin even-bedded shaly siltstone, shale, and ripple-marked fine-grained sandstone. Many of the sandstone beds range from the characteristic reddish and dark brown to a light gray. The formation is soft and easily eroded. Wherever protected by a more resistant overlying sandstone bed, it weathers as scree-covered gentle slopes marked by narrow sandstone ledges. Where unprotected it is dissected into a maze of narrow steep-sided gullies separated by sharp-crested ridges.

[2] Rock colors are from the National Research Council "Rock-Color Chart" (Goddard and others, 1948).

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The even bedding of the upper unit of the Moenkopi helps distinguish it from overlying and underlying units. Commonly the better cemented beds split into even slabs and flagstones. The poorly cemented shaly siltstone and shale beds are fissile, and they disintegrate into thin angular even-sided flakes about 1 inch on a side which form a veneer on the hillsides.

Both oscillation and current-type ripple marks are common in the sandstone, and sand-filled mud cracks are widespread in the shaly siltstone.

The upper unit of the Moenkopi is about 210 feet thick along North Cottonwood Creek. Farther west in sec. 25, T. 32 S., R. 20 E., along the west edge of Bridger Jack Mesa, the unit is about 230 feet thick (J. H. Stewart, oral communication, 1957). It is about 245 feet thick along the west edge of Lavender Creek in sec. 31, T. 31 S., R. 21 E. (E. N. Hinrichs, oral communication, 1957), a locality about 2 miles northeast of the exposures in North Cottonwood Creek (pl. 1).

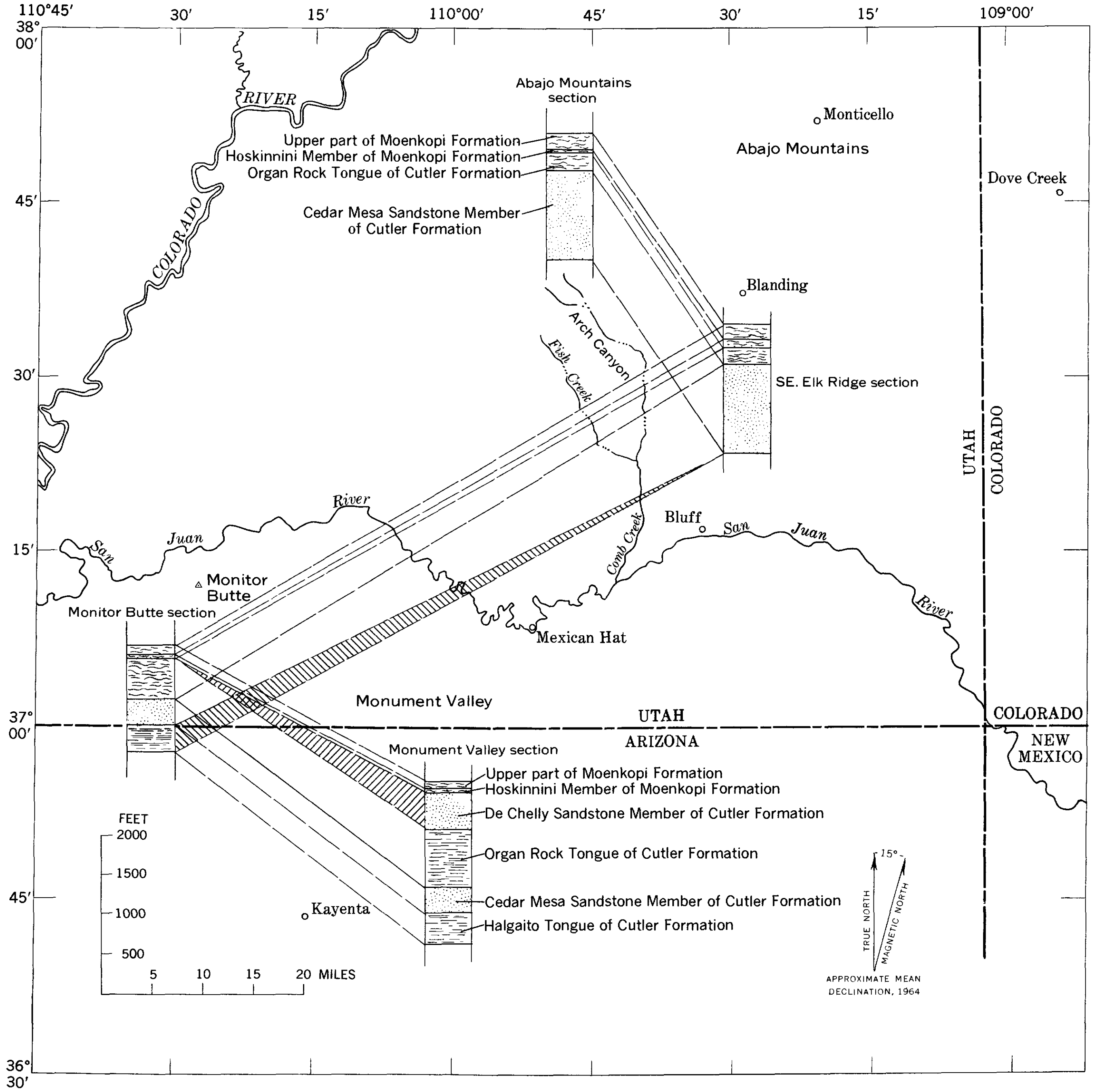


FIGURE 4.—Generalized map of southeastern Utah and northeastern Arizona showing relations among members of the Cutler Formation.

The upper unit of the Moenkopi Formation is unconformably overlain by the Chinle Formation. In the Johnson Creek dome the contact is below a thin lenticular crossbedded medium- to coarse-grained sandstone here tentatively correlated with the Shinarump Member of the Chinle Formation. Where the Shinarump is missing, the upper unit of the Moenkopi is overlain directly by mottled purple and white claystone beds of the lower unnamed member of the Chinle. Thus, along North Cottonwood Creek, the contrast between the dark-brown shaly siltstone beds of the Moenkopi and the light-gray claystone beds of the lower member of the Chinle accentuate the contact. Wherever exposed, the unconformity is undulatory, but lacks the deep conspicuous erosion channels so common farther south in the Monument Valley area.

The upper unit of the Moenkopi Formation represents terrestrial deposits formed in shallow waters on a broad flood plain that sloped westward toward the sea from highlands in western Colorado (Baker, 1933, p. 36).

TRIASSIC SYSTEM

CHINLE FORMATION

In the Abajo Mountains area, the Chinle Formation of Late Triassic age is divided into four separate lithologic units, which are, in ascending order, the Shinarump Member, a lower unnamed member, the Moss Back Member, and an upper unnamed member (table 2). These four units are well exposed in the Johnson Creek dome (pl. 1), but only the upper three are identifiable elsewhere in the Abajo Mountains area and it is assumed that the Shinarump Member was not deposited.

SHINARUMP MEMBER

Near the center of the Johnson Creek dome in the SE¼ sec. 19 and the SW¼ sec. 20, T. 34 S., R. 22 E. (unsurveyed), a thin lenticular sandstone overlies the Moenkopi Formation. This sandstone, provisionally correlated with the Shinarump Member of the Chinle Formation, forms a discontinuous ledge of irregular width mantled by float from the overlying units. In fresh exposures it is a yellowish-gray (5*Y* 8/1) massive crossbedded medium- to coarse-grained sandstone. In a few places, thin conglomerate lenses about 2 inches thick are near its base. Locally a few widely separated oval pebbles, each about half an inch long, are in a thickened sandstone lens. The crossbedding is inconspicuous and of the type commonly ascribed to stream deposits. The sandstone is well cemented; most of the sand grains are tightly enclosed in a cement of calcite, silica, and iron oxide. A few fragments of fossilized wood are in the float but none was found in place.

The Shinarump ranges in thickness from 0 to 20 feet. Commonly, it is 2 to 3 feet thick, and maintains this uniform thickness for lateral distances of 50 to 100 feet before it thickens or thins. Erosion channels, so common at the base of the Shinarump elsewhere on the Colorado Plateau, apparently were not developed in the Abajo Mountains area; they were formed, however, at the base of the Moss Back Member (p. 14.)

The contact with the overlying claystone beds of the lower unnamed member of the Chinle is gradational and some intertonguing occurs.

The Shinarump was deposited by northward-flowing streams, which rose in a highland in central and southern Arizona (McKee, 1951, p. 493–494). In the Abajo Mountains area, the lenticular character of the deposits, the small size of the contained pebbles, and the absence of channels suggest that the exposed Shinarump is near the depositional limit of these streams.

LOWER UNNAMED MEMBER

The lower unnamed member of the Chinle differs from place to place. Along North Cottonwood Creek, for example, claystone and siltstone form a light-gray (5*GY* 8/1) thin band, 5 to 20 feet thick, intercalated between the overlying clifflike Moss Back Member and the underlying dark-brown shaly siltstone beds of the Moenkopi Formation. In contrast, near the center of the Johnson Creek thick dome, correlative beds are as much as 180 feet but appear either as mottled purple and white claystone or as beds of pale-red (5*R* 6/2) intertonguing claystone and siltstone.

These strata in the lower member of the Chinle stand as a near-vertical cliff beneath the Moss Back Member. Elsewhere, especially in the Johnson Creek dome, they form a moderate slope that steepens near the overlying protective ledge of the Moss Back.

In general, the bedding is inconspicuous and vague, although locally some crossbedding is apparent.

The great variation in thickness is puzzling. Along the west edge of the mapped area, the member is about 10 feet thick; it thins to 5 feet in places and elsewhere thickens to as much as 20 feet. The pinchout of these beds is near this general locality, and the member probably ends in a concealed interval along North Cottonwood Creek near the north edge of the mapped area. Farther west, the pinchout extends through T. 32 S., R. 21 E. (E. N. Hinrichs, oral communication, 1957). The 180-foot thickness in the Johnson Creek dome must mean that the member thickens abruptly southward. A comparable thickness of 150 feet for the member is reported for the Elk Ridge area (Lewis and Campbell, 1964).

The contact with the overlying Moss Back Member is a sharp, distinct erosional unconformity, marked by an abrupt change from claystone and siltstone to coarse conglomerate. In a few localities, 1 to 3 feet of strata directly beneath the Moss Back are altered to light orange. The contact is irregular and undulatory, but overall local relief does not exceed 1 to 2 feet. In a few places the Moss Back fills broad, very shallow channels that are as wide as 300 feet but no deeper than 5 feet; the channels are cut in the uppermost strata of the lower unnamed member of the Chinle.

The intertonguing claystone and siltstone beds of these lower strata of the Chinle probably represent quiet deposition by the northward-flowing streams that deposited the Shinarump (p. 13).

MOSS BACK MEMBER

The Moss Back Member of the Chinle, one of the more resistant sedimentary units in the Abajo Mountains area, crops out as a broad hummocky bench from which most of the younger strata have been stripped. Commonly the member stands as a cliff.

The Moss Back consists of light-gray (*N* 7) massive crossbedded well-cemented lenses of conglomerate, conglomeratic sandstone, and fine- to coarse-grained sandstone.

In most places, a coarse conglomerate at the base contains well-rounded pebbles, as much as 2 inches in diameter, of red chert, red quartzite, colorless quartz, brown limy siltstone, carbonaceous fragments, and angular pieces of silicified wood. The matrix of the conglomerate is a mixture of angular to rounded, very fine- to coarse-grained quartz sand well cemented by calcite and silica. Silicified logs are common in the basal conglomerate but decrease in number upward. This basal conglomerate ranges in thickness from a few inches to as much as 10 feet.

Conglomeratic sandstone beds, which locally overlie the basal conglomerate, alternate at irregular intervals with the sandstone lenses. Laterally these beds and lenses intertongue and grade into one another in distances as short as 5 feet. In a few places claystone lenses are intercalated.

In the sandstone lenses, the cross-strata sets are short and markedly concave and of the type commonly ascribed to stream deposition. Most grains are angular (some as a result of quartz overgrowths) and about 0.20 mm in diameter (fine-grained), although the range is from 0.01 mm to as much as 1.00 mm. Calcite is the dominant cement; silica and iron oxide are present in lesser amounts. Isolated pebbles are common. Locally some of these pebbles form small thin irregular lenses about 2 feet long and 4 inches thick, which break the continuity of the sandstone.

Carbonaceous streaks and clay partings are common through the entire unit. Some of the carbonaceous streaks are 6 to 10 feet long and 1½ to 3 inches thick although most are smaller. The angular clay partings are 6 to 8 inches long and 2 to 3 inches thick, and are alined in crude bedding planes.

Much of the Moss Back Member is stained by limonite. This staining is selective, certain beds containing much limonite and others being almost limonite free.

The following section of the Moss Back Member is exposed along North Cottonwood Creek.

Section of Moss Back Member of Chinle Formation measured in sec. 28, T. 32 S., R. 21 E., near Wilson Ranch

	Ft	in.
Triassic:		
Chinle Formation:		
Upper unnamed member.		
Moss Back Member:		
Sandstone, light-brown, massive, locally platy, crossbedded; composed of fine- to medium-grained quartz sand in a tight cement of calcite and silica; local intercalated conglomerate lenses; cliff former	52	4
Conglomeratic sandstone, light-brown to brown, platy to massive, slightly friable; moderately well cemented by calcite and silica	3	0
Sandstone and conglomeratic sandstone, light-gray, massive, crossbedded, well-cemented; weathers to blocky ledgelike layers	14	8
Conglomerate, dark-gray; composed of pebbles of well-rounded chert, quartzite, quartz, and limy siltstone in a matrix of very fine to coarse-grained quartz sand; well cemented by calcite and silica	8	2
Total Moss Back Member	78	2
Lower unnamed member.		

The Moss Back Member is between 50 and 100 feet thick in the Abajo Mountains area. It thins northward, however, and pinches out along a northwest-trending line near Moab, Utah (Stewart, 1957, p. 455). It thickens erratically to the southwest and reaches a maximum thickness of about 200 feet in a few places in the White Canyon area, Utah (R. E. Thaden, oral communication, 1956).

The contact with the overlying upper unnamed member of the Chinle is gradational, and in a few places the units intertongue. The contact is accentuated by the sharp topographic break between the bench formed on the Moss Back and the moderate to steep slopes formed on the uppermost Chinle strata.

Resurgence of the northward-flowing streams that deposited the Shinarump (p. 13) probably was responsible for the deposition of the Moss Back. A study of the direction of sediment transport suggests that much of the Moss Back was formed by northwest-flowing streams (Poole and Williams, 1956, p. 231). It appears likely, however, that in the area now occupied by the Abajo Mountains and Elk Ridge, there may have been local variations in stream directions, for the sedimentary trends in this general area suggests a northeastward source (Poole and Williams, 1956, fig. 50B). This same northeastward source is suggested in both the Moab-Interriver area (E. N. Hinrichs, oral communication, 1957) and the Elk Ridge area (Lewis and Campbell, 1964).

UPPER UNNAMED MEMBER

The upper unnamed member of the Chinle is well exposed both along North Cottonwood Creek and in the Johnson Creek dome. In both localities these strata stand as moderate to steep, intricately dissected slopes between the broad benches formed by the Moss Back and the sheer cliffs formed by the overlying Wingate Sandstone (Upper Triassic).

The two localities are only about 12 miles apart, but strata undergo an unusual change in color and lithology in that distance. At North Cottonwood Creek the strata consist of about 400 feet of variegated bentonitic claystone, moderate reddish-brown (10*R* 5/6) siltstone, and fine-grained sandstone—all cemented by calcite. The units alternate in an irregular sequence, intertongue, and grade into each other laterally. Most of the claystone beds are either pale red, violet, green, gray, or orange, or a combination of these colors. Commonly the claystone beds are massive and structureless. On outcrop, their surface takes on a frothy or popcornlike appearance. In contrast, the strata exposed in the Johnson Creek dome are a moderate reddish brown (10*R* 5/6) and consist of about 570 feet of siltstone and sandstone and a few yellowish-gray (5*Y* 8/1) limestone beds. The clastic rocks are thin bedded, horizontally laminated, and extremely fissile. Bentonitic claystone, very common in North Cottonwood Creek, is absent from this area.

Commonly the siltstone and sandstone in both localities are moderate reddish brown (10*R* 5/6), thin bedded, platy, locally structureless, and composed of angular quartz grains poorly to moderately well cemented by calcite. Most of the grains in the siltstone are about 0.05 mm in diameter and have a thin coat of iron oxide. The very fine grained sandstone consists chiefly of angular quartz grains 0.08 mm in diameter similarly coated with iron oxide.

Along North Cottonwood Creek the alternating sequence of claystone, siltstone, and sandstone, has, about 70 feet below its top, a pale-red (5*R* 6/2) bed, about 5 feet thick, of extremely well indurated conglomeratic sandstone. This bed thickens and thins erratically and locally grades into a fine-grained sandstone. The pebbles are chiefly oval, well rounded, and as much as 4 inches in long diameter, and include such varied lithologic types as quartz, quartzite, chert, limy siltstone, and claystone. The varicolored pebbles form a bright mosaic in a well-cemented sandstone matrix. This matrix consists chiefly of angular, very fine (0.08 mm) quartz grains which enclose well-rounded quartz grains (0.66 mm), all tightly cemented by silica and some calcite.

The following section of the upper unnamed member of the Chinle is exposed along North Cottonwood Creek.

Section of the upper unnamed member of the Chinle Formation measured in sec. 28, T. 32 S., R. 21 E., near Wilson Ranch

	Ft	in
Triassic:		
Wingate Sandstone.		
Chinle Formation:		
Upper unnamed member.		
Sandstone, moderate reddish-brown, platy, crossbedded, fine-grained; cliff former	20	4
Sandstone, moderate reddish-brown, fissile, even-bedded to crossbedded, fine-grained; forms steep slopes	42	2
Sandstone, pale-red, massive, locally platy, fine-grained; cliff former	11	2
Conglomerate and conglomeratic sandstone, pale-red, massive, crossbedded; contains rounded pebbles of quartz, quartzite, chert, limy siltstone, and claystone in a matrix of fine-grained sandstone well cemented by silica and some calcite. Pebbles, as much as 4 in. long, imbricated parallel to the bedding planes. Locally unit grades laterally into reddish-brown massive fine-grained sandstone	5	0
Siltstone, moderate reddish-brown, shaly; intercalated local sandstone lenses; forms slopes	18	8
Sandstone, moderate reddish-brown, massive, fine-grained; well cemented by calcite; cliff former	7	6
Siltstone, moderate reddish-brown, fissile; forms shaly partings; intercalated local sandstone lenses; forms slopes	10	6
Siltstone and fine-grained sandstone, moderate reddish-brown, commonly massive but locally platy; well cemented by calcite. In places, mottled by elongate light-gray blebs that parallel the bedding planes	10	2
Siltstone, moderate reddish-brown, fissile in places; forms ledgy slopes; resistant ledges firmly cemented by calcite	82	0

Section of the upper unnamed member of the Chinle Formation measured in sec. 28, T. 32 S., R. 21 E., near Wilson Ranch—Continued

	Ft	in
Triassic—Continued		
Chinle Formation—Continued		
Upper unnamed member—Continued		
Claystone, light-gray, green, pale-red, and orange-brown, massive; locally structureless, but even to cross bedded elsewhere. Forms round hummocky slopes more or less concealed beneath talus	134	4
Claystone, siltstone, and fine-grained sandstone; partly concealed beneath slope wash and colluvium. At base moderate reddish-brown shaly siltstone intertongues with dark-gray platy crossbedded fine- to coarse-grained sandstone of uppermost strata of the Moss Back	61	6
Total upper unnamed member	403	4
Moss Back Member.		

In the Johnson Creek dome the upper unnamed member of the Chinle is well exposed along the north rim. In this report, it is considered as a single unit; however, J. H. Stewart (written communication, 1954) of the Geological Survey correlated the lower 437 feet with the Owl Rock Member of the Chinle Formation and the remaining overlying 131 feet with the Church Rock Member of the Chinle Formation. Listed below is a modified section of the upper unnamed member of the Chinle measured near the head of Johnson Creek by Stewart and his colleagues.

Section of upper unnamed member of Chinle Formation measured near head of Johnson Creek, SE¼ sec. 23, T. 34 S., R. 22 E.

	Ft	in
Triassic:		
Wingate Sandstone.		
Chinle Formation:		
Church Rock Member:		
Siltstone, sandy, to sandstone, pale red, well cemented, noncalcareous; locally ripple laminated	22	6
Siltstone and sandy siltstone; grayish-red; stratification concealed; well cemented, slightly calcareous in parts; forms steep slope	55	10
Sandstone, pale-red; composed of thin sets of laminae; very fine grained, firmly cemented, calcareous; forms steep ledgy slope	52	5
Total Church Rock Member	130	9
Owl Rock Member:		
Siltstone and limestone, pale reddish-brown to pale-red; siltstone is well cemented, calcareous, and structureless; limestone is dense, horizontally laminated to thinly bedded. Unit forms vertical cliff in basal 15 ft and steep slope above	44	1

Section of upper unnamed member of Chinle Formation measured near head of Johnson Creek, SE¼ sec. 23, T. 34 S., R. 22 E.—Continued

	Ft	in
Triassic—Continued		
Chinle Formation—Continued		
Owl Rock Member—Continued		
Siltstone, pale reddish-brown, well cemented, calcareous, structureless; weathers to form steep rubble-covered slope	68	6
Siltstone, pale-red, well-cemented, calcareous, structureless; contains intercalated, very fine grained sandstone lenses and thin beds of limy siltstone pebbles	30	11
Siltstone, grayish-red, poorly to well cemented, calcareous; stratification concealed; forms steep ledgy slope	85	3
Siltstone, sandy, and sandstone; grayish-red, well cemented, calcareous, structureless; weathers to gentle slope. Sandstone has minor thin sets of horizontal beds; weathers to vertical cliff	26	5
Limestone, pale-red; composed of very thin to thick horizontal beds; weathers to form steep ledgy slope	11	0
Siltstone, dark reddish-brown, poorly to firmly cemented; stratification concealed; forms steep rubble-covered slope	153	8
Sandstone, silty, grayish-red, well-cemented, calcareous; composed of subangular reddish-brown quartz grains	5	2
Siltstone, claystone, silty, grayish-red, poorly cemented, noncalcareous; unit forms slope	11	10
Total Owl Rock Member	436	10
Moss Back Member.		

In North Cottonwood Creek, the contact between the upper unnamed member of the Chinle and the overlying Wingate is arbitrarily selected below a reddish-brown medium-grained sandstone that contains many coarse, frosted quartz grains. The large size of the sand grains (0.35 mm) in the basal strata of the Wingate contrasts with the small grain size in the uppermost part of the Chinle (0.04 mm).

In the Johnson Creek area, the marked contrast in grain size is a local feature, only some zones in basal strata of the Wingate having abundant medium to very coarse grains of rounded and frosted quartz. For the most part, the contact is emphasized by a color change from the reddish brown characteristic of the Chinle to the orange brown so distinctive of the Wingate. In detail, however, the change is not marked, for in many places the siltstone beds of the Chinle grade into a very fine to fine-grained sandstone in the basal part of the Wingate, remarkably similar to some beds in the Chinle.

The intertonguing of the claystone, siltstone, and limestone beds of the upper unnamed member of the

Chinle suggests rapidly changing conditions of sedimentation. At one stage, stream deposition prevailed and silt and fine sand were deposited. As the streams dwindled and the region became more desertlike, clay was deposited and, in the playa lakes, carbonates settled out. As the arid conditions gradually spread, the deposition of eolian silt and very fine grained sand destroyed the lakes and buried the lacustrine deposits. These silt and sand deposits were the forerunners of the huge sand accumulations that comprise the Wingate and Navajo Sandstones. Several cross-stratification studies made in units correlated with the upper unnamed member of the Chinle indicate that the transport was from the southeast (Stewart and others, 1959, p. 523).

GLEN CANYON GROUP

In the Abajo area the Glen Canyon Group consists of three formations which are, in ascending order, the Wingate Sandstone of Late Triassic age, commonly a reddish-brown massive cliff-forming crossbedded sandstone; the Kayenta Formation, a pale-red uneven-bedded bench-former of Late Triassic(?) age; and the Navajo Sandstone of Triassic(?) and Jurassic age, a very pale orange massive crossbedded sandstone similar in many respects to the Wingate. In the Abajo Mountains area, these formations are conformable and their contacts are gradational.

These three units are widespread in the mapped area, and commonly their mode of outcrop is distinctive. The Wingate Sandstone generally stands as a sheer cliff that extends for miles. The Kayenta forms an irregular steplike steep slope or bench which supports a sparse growth of piñon pine, juniper, and other scrubby evergreens. The Navajo crops out as a sheer cliff if protected by the overlying, more resistant Carmel Formation (Middle and Upper Jurassic), or as hummocky knobs if erosion has removed the protective cover.

WINGATE SANDSTONE

The Wingate Sandstone, lowest formation of the Glen Canyon Group, is exposed chiefly in the northwest corner of the mapped area, where it forms the canyon walls of Indian, Titus, and North Cottonwood Creeks. It also crops out in the rim of the dissected Johnson Creek dome. In most places the unit stands in its full thickness as a sheer vertical cliff, although in the western part of the Johnson Creek dome it weathers to form moderate to steep slopes covered by a dense growth of scrub oak. It ranges from pale yellowish brown (10*YR* 7/3) to moderate reddish brown (10*R* 4/6) and is a massive crossbedded, very fine to fine-grained quartzose sandstone. It is friable and is weakly to moderately well cemented by calcite and some silica and iron oxide. The formation is composed of large-scale trough sets of cross-strata that, in many places, are masked by streaks of desert varnish.

The grains, which are chiefly quartz and minor amounts of microcline, are coated with iron oxide and range from angular to subround; the angularity of some quartz grains is due to quartz overgrowths. The unit is well sorted; most of the grains are about 0.15 mm in diameter, although they range from 0.04 to about 0.2 mm. Locally the basal 2 to 3 feet of the Wingate contains an abundance of medium to very coarse frosted and rounded quartz grains (p. 16).

In the Abajo Mountains area, the Wingate is about 240 feet thick. To the north in the Moab-Interriver area, the formation ranges in thickness from 280 to 310 feet (E. N. Hinrichs, oral communication, 1957), and to the southwest on Elk Ridge, the Wingate is about 250 feet thick (Lewis and Campbell, 1964).

The contact of the Wingate Sandstone with the overlying Kayenta Formation is gradational, and locally the two formations intertongue. Baker (1933, p. 43) reported that in the Moab area, basal strata of the Kayenta resemble the uppermost units of the Wingate.

The Wingate Sandstone was deposited in a huge oblong form that covers most of the Four Corners area (Baker, Dane, and Reeside, 1936, p. 52); the Abajo Mountains area is near the center of this oblong.

The large-scale tangential crossbedding in the Wingate indicates the persistence of the arid conditions that began in late Chinle and continued through Wingate time. A few orientation studies of the crossbedding in the Wingate Sandstone suggest that the sands were transported from the northwest (Stewart and others, 1959, p. 524).

TRIASSIC(?) SYSTEM

KAYENTA FORMATION

Conformably overlying the Wingate Sandstone are the pale- to dark-red, irregularly bedded fine- to coarse-grained sandstone beds of the Kayenta Formation, the middle unit of the Glen Canyon Group. The Kayenta, best exposed in the northwest corner of the mapped area, chiefly along Indian, Titus, and North Cottonwood Creeks, also crops out to the southwest in the walls of Deep, Mule, and Allen Canyons. Exposures of the Kayenta in the rim of the Johnson Creek dome are somewhat concealed by talus and dense vegetation.

Kayenta strata are resistant and normally weather as a ledgy bench which acts as a protective cap for the softer, more friable, underlying Wingate Sandstone. In gross aspect the Kayenta is characterized by ledgy low-angle slopes, a distinctive pale-red tinge, and uneven bedding—features which distinguish it from the underlying Wingate and the overlying Navajo.

On fresh exposures the sandstone beds range from pale red (10*R* 6/2) to moderate reddish orange (10*R* 6/6), although on weathered surfaces these units take on darker values. The sandstone beds are uneven and locally crossbedded, and range in thickness from 1 inch to as much as 30 feet. Irregularly interbedded with the sandstones are lenses of dark-gray massive structureless claystone and reddish-brown crossbedded conglomeratic sandstone; none persist very far laterally.

The sandstone is composed of angular to well-rounded grains of quartz, small amounts of microcline, and minor accessory minerals. Some quartz grains have thin quartz overgrowths; all grains are coated with iron oxide. Silica is the dominant cement, although calcite serves as a secondary cement in a few sandstone lenses. The sand grains range from 0.04 to 0.55 mm in diameter, but most are about 0.20 mm.

Because the Kayenta intertongues with both the underlying Wingate Sandstone and the overlying Navajo Sandstone, thickness measurements vary widely. In the Abajo Mountains area, the Kayenta is about 185 feet thick. To the north in the Moab-Interriver area the Kayenta is about 220 feet thick (E. N. Hinrichs, oral communication, 1957), and in the Elk Ridge area it ranges in thickness from about 100 to about 260 feet (Lewis and Campbell, 1964).

The irregularly interleaved claystone and conglomerate beds in the crossbedded sandstone suggest that streams began to spread their detritus as the desertlike conditions that prevailed during Wingate time began to moderate. The streams, confined to the margins of the depositional basin in which the Wingate was formed, were reactivated at this time and spread their sedimentary load ever more widely until a new onset of arid conditions, represented by the Navajo Sandstone, again forced their withdrawal (Baker, Dane, and Reeside, 1936, p. 53). Sedimentary studies suggest that some of these streams rose in low-lying highlands to the north and northeast (Stewart and others, 1959, p. 524).

TRIASSIC(?) AND JURASSIC SYSTEMS

NAVAJO SANDSTONE

The uppermost formation of the Glen Canyon Group is the Navajo Sandstone, a very pale orange (10*YR* 8/2) massive crossbedded fine- to medium-grained, quartzose sandstone. It is well exposed on the flanks of Shay Mountain and along the west edge of the mapped area but poorly exposed in the Johnson Creek dome, where it forms a major part of the rim.

Where the Navajo is protected by the resistant cap of the Carmel Formation, it stands as a sheer vertical cliff; where the Carmel has been stripped back, the Navajo weathers to hummocky knobs separated by deep narrow ravines.

The Navajo is remarkably consistent in character, appearing in most outcrops as a very pale orange sandstone that locally alters to a yellowish gray (5*Y* 8/1). It is massive and is marked by long, sweeping, tangential sets of cross-strata—a mark of eolian deposition. Commonly the unit is poorly cemented and friable; however, near igneous intrusions, a zone about 3 feet thick is metamorphosed to a resistant quartzite.

The Navajo is composed chiefly of subround to round frosted quartz grains which range from 0.05 to 0.36 mm in diameter, most being about 0.15 mm. In general, the sandstone is well sorted. Quartz overgrowths are on some quartz grains, and all are covered by a thin film of iron oxide. The principal cement is silica, although calcite and iron oxide also act as binding agents. Several limy sandstone beds, most of them about 4 feet thick and of limited lateral extent are near the top of the Navajo Sandstone. In these, calcite is the dominant cement; in some, the sand grains are so few and so widely separated that the beds are best described as sandy limestone. These resistant limestone beds bevel the underlying strata and act as cap rocks on many of the low benches northeast of Shay Mountain.

The Navajo Sandstone is about 410 feet thick in the Abajo Mountains area and of similar thickness in the Moab-Interriver area to the north (E. N. Hinrichs, oral communication, 1957).

The contact of the Navajo Sandstone with the overlying Carmel Formation is distinct wherever exposed in the mapped area and is interpreted to be an unconformity of wide extent. It appears as an undulatory plane of slight relief which truncates the crossbedded Navajo Sandstone. Baker (1933, p. 47) referred to the surface as a "slightly irregular floor," and suggested that this slight relief may indicate a period of erosion prior to the deposition of the Carmel Formation.

The Navajo Sandstone was deposited under arid conditions similar to those that prevailed during deposition of the Wingate. Streams that had been active during Kayenta time disappeared and their deposits were gradually buried by a huge accumulation of wind-worked sand (Navajo Sandstone) which covered most of what is now southeastern Utah and northeastern Arizona. Near the end of this arid episode, local ephemeral playa lakes formed, in which the sandy limestone beds at the top of the Navajo were deposited (Baker, Dane, and Reeside, 1936, p. 53). Sedimentary-structure studies indicate that the cross-strata dip southeast, and imply that the dominant wind direction was from the northwest (Stewart and others, 1959, p. 525).

JURASSIC SYSTEM

SAN RAFAEL GROUP

In the Abajo Mountains area, the San Rafael Group consists of three formations which are, in ascending order, the Carmel Formation, the Entrada Sandstone, and the Summerville Formation (table 2). The Carmel Formation represents the first advance of the Carmel sea (Baker, Dane, and Reeside, 1936, p. 54) into this region. A temporary withdrawal of this sea accompanied by a renewal of arid conditions resulted in the deposition of the wind-worked Entrada Sandstone. A subsequent readvance of the sea furnished the sediments that now constitute the Summerville Formation.

CARMEL FORMATION

As yet, no unanimity of opinion exists as to which strata should be included in the Carmel Formation of Middle and Late Jurassic age. Baker (1933, p. 48) considered the Carmel of the Moab district to consist of 20 to 70 feet of soft red thin-bedded sandstone, mudstone, and sandy shale. In the Abajo Mountains area, however, the Carmel changes markedly in lithology and color as it is traced across the mountains. Along the northeast flank of the mountains the Carmel is about 110 feet thick and includes four distinct lithologic units (figs. 5, 6A). At the base is a reworked zone consisting of a pale grayish-orange massive fine-grained sandstone 5 to 15 feet thick that truncates the Navajo Sandstone. Directly overlying the reworked zone is about 8 feet of pale reddish-brown thin-bedded shaly siltstone and very fine grained sandstone called the lower red. Overlying this is a very pale orange massive crossbedded, very fine grained sandstone, about 40 feet thick, called the middle sandstone. The uppermost unit, called the upper red, is about 50 feet thick and consists of moderate reddish-orange massive to platy, fine- to medium-grained sandstone and shaly siltstone.

Along the southwest flank of the mountains, the two distinctive red beds disappear, and here the Carmel is separated only with difficulty from the underlying Navajo and the overlying Entrada Sandstone. Because of this difficulty, I have locally, and especially in the southwest corner of the mapped area, included strata in the Navajo which are elsewhere assigned to the Carmel.

Thus, all four units of the Carmel crop out in the northern part of the mapped area, but on the southwest flank of the mountains, near the Causeway (pl. 1), only the two sandstone units are found. To the south along Butler Wash, beyond the limit of the mapped area, all four units of the Carmel are again exposed (R. Q. Lewis Sr., oral communication, 1957).

In the Abajo Mountains area, the Carmel is well exposed along the flanks of Shay Mountain, on the steep northwest-facing escarpment that forms the east wall of Harts Draw, and in the many canyons along the west side of the mapped area (pl. 2).

Reworked zone.—The reworked zone at the base of the Carmel Formation is a pale grayish-orange (10*YR* 7/4) massive even- to cross-bedded friable, very fine grained sandstone (fig. 6*B*). In a few places, white angular chert nodules, an eighth to a quarter of an inch in diameter, are scattered irregularly through the basal part of this sandstone. Similar

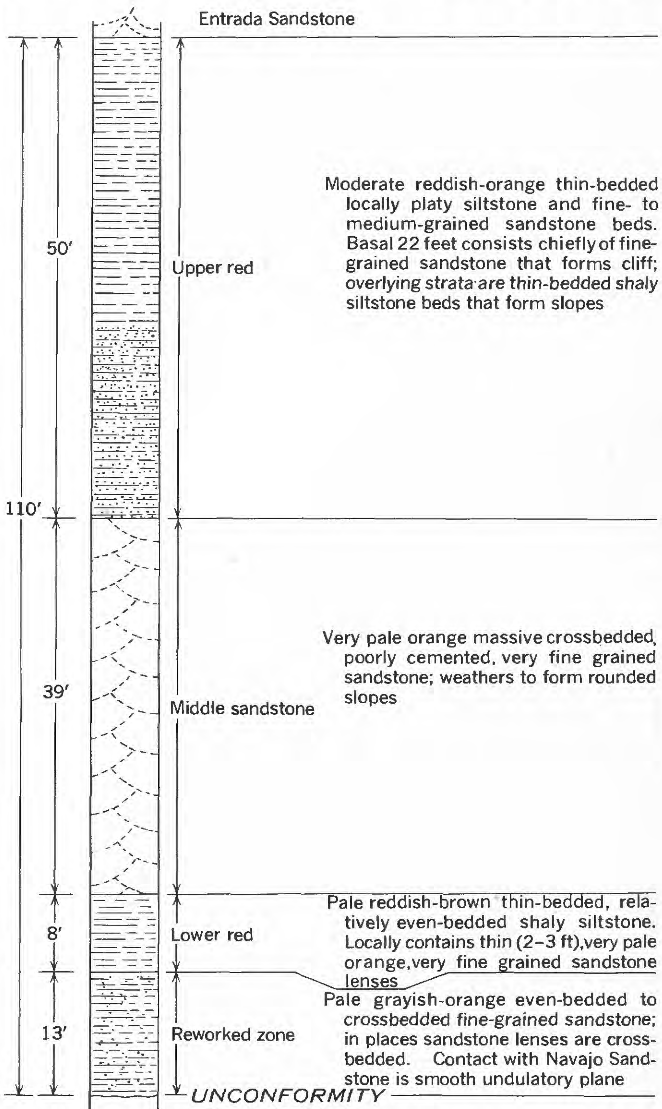


FIGURE 5.—Measured section of the four lithologic units included in the Carmel Formation as exposed along the northeast flank of the Abajo Mountains.

nodules are in the upper 3 to 6 feet of the Navajo Sandstone. The sandstone of the reworked zone consists chiefly of quartz grains that are about 0.12 mm in diameter and range from angular to subround. They are poorly cemented by calcium carbonate, silica, and iron oxide. Scattered irregularly through this very fine grained sandstone matrix are well-rounded quartz grains about 0.25 mm in diameter. The reworked zone ranges in thickness from about 5 to about 15 feet; it thickens and thins irregularly. The unconformable contact with the underlying Navajo Sandstone is undulatory, and relief locally is about 6 inches in 100 feet.

Lower red.—Overlying the reworked zone is about 8 feet of pale reddish-brown (10*R* 5/4) thin even-bedded shaly sandy siltstone beds that constitute the lower red (fig. 6*C*). Intercalated in the siltstone are very pale orange (10*YR* 8/2) thin-bedded, very fine grained

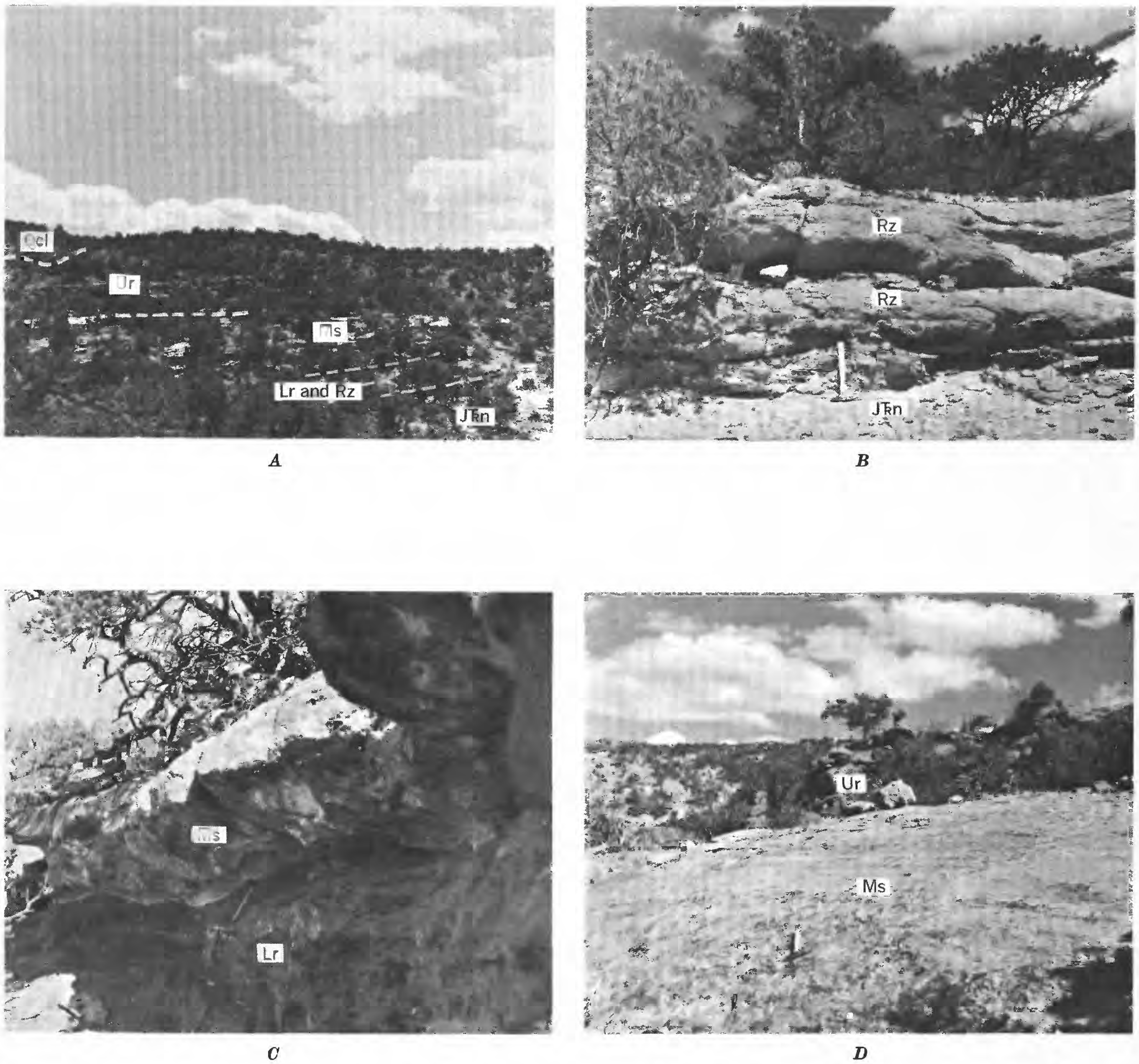


FIGURE 6.—Photographs of the Carmel Formation as exposed in the northern part of the Abajo Mountains area. *A*, View of the four units of the Carmel Formation (JTRn, Navajo Sandstone, Rz, reworked zone of the Carmel; Lr, lower red; Ms, middle sandstone; Ur, upper red. Qcl, colluvium. *B*, Closeup photograph showing the relations of the reworked zone (Rz) that forms the basal part of the Carmel to the Navajo Sandstone (JTRn). The hammer head rests on the Navajo Sandstone and the handle rests on the reworked zone. *C*, Closeup view of the undulatory contact of the lower red (Lr) (dark-gray) and the overlying middle sandstone (Ms) (light-gray). *D*, View of middle sandstone (Ms). Dark-gray ledge in background is formed by the upper red (Ur).

sandstone lenses. The lower red is fissile and commonly forms low-angle slopes covered by a scree of angular shaly fragments. The grains of two sizes common in the reworked zone are also in the lower red but include fewer large grains. Cementing agents again are calcite, silica, and iron oxide.

The lower red, which thickens and thins erratically, ranges in thickness from about 5 to 15 feet. Its contact with the middle sandstone is undulatory, the maximum relief along the contact being about 2 feet (fig. 6*C*).

Commonly the reworked zone and the lower red stand as a unit, 5 to 25 feet high, that forms a steep slope between the massive underlying Navajo Sandstone and the bench formed by the middle sandstone, (fig. 6*A*).

Middle sandstone.—Overlying the lower red is the middle sandstone (fig. 6*D*), a very pale orange (10*YR* 8/2) massive crossbedded friable fine-grained sandstone. It weathers either as a steep slope or as a hummocky bench that can be traced for miles. It is composed chiefly of subround to well-rounded quartz grains which range from 0.04 mm to 0.50 mm in diameter, most of the grains being about 0.25 mm. The sandstone is weakly cemented by calcite, silica, and iron oxide. This middle sandstone is 30 to 50 feet thick, and in most places is about 40 feet thick. The contact with the overlying red beds is sharp.

Upper red.—The uppermost unit of the Carmel, the upper red, is a moderate reddish-orange (10*R* 6/6) massive, very fine grained sandstone in its lower half and a thin-bedded shaly siltstone in its upper half. The lower sandstone unit is well cemented by calcium carbonate and commonly stands as a nearly vertical cliff (fig. 6*A*). The shaly siltstone is more easily eroded and forms low-angle scree-covered slopes. The sandstone is composed chiefly of angular to subround quartz grains that are about 0.10 mm in diameter. Scattered irregularly through this sandstone matrix are well-rounded quartz grains about 0.40 mm in diameter. This upper red unit is about 50 feet thick.

The contact with the overlying moderate yellowish-orange (10*YR* 7/6) sandstone of the basal part of the Entrada Sandstone is gradational—the beds of reddish-orange shaly siltstone grade into a darker reddish-orange massive crossbedded fine-grained sandstone, which in turn grades into the very pale-orange of the Entrada Sandstone.

The following section of the Carmel Formation gives details of the four units.

Section of the Carmel Formation measured along the east valley wall of Harts Draw in sec. 35, T. 32 S., R. 22 E.

	Feet
Jurassic:	
Entrada Sandstone.	
Carmel Formation:	
Upper red:	
Sandstone, moderate reddish-orange (10*R* 6/6), massive, very fine grained in lower half; similarly colored siltstone in upper half	41
Middle sandstone:	
Sandstone, very pale-orange (10*YR* 8/2), fine-grained, massive, crossbedded, extremely friable; weathers to form steep slope	33
Lower red:	
Silstone, pale reddish-brown (10*R* 5/4), thin- and even-bedded; contains intercalated very pale orange (10*YR* 8/2) massive thin-bedded, very fine grained sandstone lenses	10
Reworked zone:	
Sandstone, pale grayish-orange (10*YR* 7/4), very fine grained, massive, even- to cross-bedded, friable	6
Total Carmel Formation	90
Unconformity.	
Jurassic and Triassic (?):	
Navajo Sandstone.	

This section is representative of most exposures of the fourfold division of the Carmel Formation. Other exposures differ chiefly in the thicknesses of the individual units, particularly the middle sandstones and the upper red. Near the Causeway (pl. 2), along the west edge of the area, the Carmel consists of only the two sandstone units. The following section measured along the west valley wall of Dry Wash is characteristic.

Section of the Carmel Formation measured along the west valley wall of Dry Wash in sec. 25, T. 34 S., R. 21 E. (unsurveyed)

	Feet
Jurassic:	
Entrada Sandstone.	
Carmel Formation:	
Middle(?) sandstone:	
Sandstone, light brown (5*YR* 7/4), fine-grained, massive, crossbedded; locally contains lenses of grayish-brown (5*YR* 3/2) crossbedded fine- to medium-grained sandstone	18
Reworked(?) zone:	
Sandstone, moderate reddish-brown (10*R* 5/6), very fine grained, massive, even-bedded to poorly crossbedded; discrete angular chert nodules, an eighth to a quarter of an inch in diameter, in basal strata; slightly undulatory contact with underlying Navajo Sandstone	16
Total Carmel Formation	34
Unconformity.	
Jurassic and Triassic(?):	
Navajo Sandstone.	

The Carmel Formation thins to the south. Along Harts Draw, in the northeast corner of the mapped area, the formation ranges in thickness from 75 to 120 feet. Southward near the head of Tuerto Canyon, it is about 80 feet thick. Along the southwest flank of the mountains, where the Carmel consists of the two light-colored sandstone units, it is about 35 feet thick.

The contact of the Carmel Formation with the overlying Entrada Sandstone is gradational and is generally placed along an ill-defined plane where the sandstone of the upper red unit changes from reddish orange to very pale orange. Locally in the southwest part of the mapped area, a light-brown (5*YR* 6/4) massive lenticular ledge of sandstone about 6 feet thick was selected as the top of the Carmel. Where this sandstone is absent, however, a zone 10 to 15 feet thick between obvious Carmel and Entrada strata was mapped as the top of the Carmel.

Presumably the Carmel sea advanced across this region from the northwest (Baker, Dane, and Reeside, 1936, p. 54), truncated and reworked the top of the Navajo Sandstone, and included its detritus in the sediments which now form the reworked zone. During this first inundation by the Carmel sea, an ancestral high probably began to rise slowly in the region centering about the Causeway (pl. 1), and forced a slight withdrawal of the sea. In the areas covered by the sea, the lower red was deposited; the shoreline of that sea may be reflected by the pinchout of the lower red. During a temporary, minor, and possibly purely local withdrawal of the sea, arid conditions prevailed and sands spread thickly and rapidly enough to bury the rising highland. These sands now form the middle sandstone. When the winds abated and the arid conditions moderated, the Carmel sea readvanced until it reached the margins of the slowly rising highland. Sediments of the upper red were deposited at this time, and the pinchout of this unit marks the shoreline of this ancestral sea.

ENTRADA SANDSTONE

In the southern part of the Abajo Mountains area, the Entrada Sandstone is subdivided into two parts, a lower massive crossbedded sandstone called the lower unit of the Entrada Sandstone, and an upper unit, the Moab Sandstone Member (table 2), which correlates with the Moab Tongue of the Entrada Sandstone (p. 23). As these two units are traced northward, the differences between them lessen and, on the north flank of the mountains, the Moab Sandstone Member cannot be distinguished with certainty from the lower unit. Consequently the two units are mapped together in that area.

The Entrada Sandstone, the middle formation of the San Rafael Group, is exposed chiefly on the north and west flanks of the Abajo Mountains. It crops out in Harts Draw, on the flanks of Shay Mountain, along the valley walls of Tuerto Canyon, and in the dissected rim of the Johnson Creek dome.

In most places the Entrada Sandstone is a very pale orange (10*YR* 8/2) massive friable crossbedded, very fine to medium-grained sandstone. Around the flanks of Shay Mountain, the basal part of the Entrada commonly is a moderate reddish brown in contrast to the upper part which is a very pale orange. The Entrada closely resembles the other crossbedded sandstone units, except that it is banded. Its massiveness is broken by thin planes, probably bedding planes, that divide the Entrada into beds, each about 30 feet thick and each composed of intricately crossbedded sets of strata. These bedding planes are not continuous but new ones appear at different horizons, to produce the gross banded appearance.

The sandstone beds in the Entrada are composed chiefly of angular to well-rounded quartz grains that range from about 0.05 to 0.3 mm in diameter, most of the grains being about 0.15 mm. The sandstone beds are weakly cemented by calcite, silica, and iron oxide.

Near the south edge of the mapped area, the Entrada can be subdivided into three units, but the differences between these units do not persist in the Abajo Mountains area and the units cannot be traced northward. South of the mapped area, however, in Butler Wash, the three units are more distinctive and there the Entrada consists of two sandstone units (a lower and upper "slick-rim") separated by a reddish-brown shaly siltstone.

The following section measured along the valley walls of Dry Wash shows the threefold division of the Entrada in the southern part of the Abajo Mountains area.

Section of Entrada Sandstone measured along valley walls of Dry Wash in sec. 2, T. 35 S., R. 21 E. (unsurveyed)

	Feet
Jurassic:	
Summerville Formation.	
Entrada Sandstone:	
Sandstone, very pale orange (10*YR* 8/2) to grayish-orange (10*YR* 7/4), massive, crossbedded, very fine to fine-grained; forms steep escarpment (upper slick-rim sandstone)	51
Siltstone, shaly, moderate reddish-brown (10*R* 4/6), thin-bedded, fissile; contains lenses of moderate reddish-brown fine- to medium-grained sandstone; unit commonly forms low-angle steplike bench	63
Sandstone, grayish orange-pink (10*R* 8/2) to moderate orange-pink (10*R* 7/4), massive, crossbedded, fine-grained; forms ledge locally concealed by slope wash (lower slick-rim sandstone)	6
Total Entrada Sandstone	120
Carmel Formation.	

The lower unit of the Entrada Sandstone, along the south flank of the mountains, is about 120 feet thick and is overlain by about 45 feet of the Moab Sandstone Member. Farther north around the flanks of Shay Mountain, where these two units cannot be discriminated, the Entrada Sandstone is about 170 feet thick.

The Entrada Sandstone represents sediments deposited during an episode of extreme aridity following a major withdrawal of the Carmel sea from this region. The local temporary fluctuations of the sea, represented by the fourfold division of the Carmel Formation, may have been minor manifestations of an impending major retreat that occurred at the end of Carmel time. As the sea withdrew, clean windworked sand, which had been deposited along the margins of sea, spread over the newly exposed plain, and in time the entire region became a desert marked by shifting dunes.

MOAB SANDSTONE MEMBER

Baker (1933, p. 49) reported that, in the Moab district, the Entrada can be subdivided into two units. The upper unit is "a single massive crossbedded grayish-white bed 90 to 100 feet thick and separated from the rest of the Entrada Sandstone by a definite bedding plane." He and his associates (Baker and others, 1927, p. 804) accepted a name proposed by W. T. Lee in an unpublished report, and called the bed the Moab Tongue of the Entrada Sandstone. E. T. McKnight noted (Baker, 1933, p. 50) that, west of the Moab district, the shale parting that underlies the Moab Tongue thickens and becomes identical in lithology with the Summerville. In the southern part of the Abajo Mountains area a very pale orange (10YR 6/2) even-bedded fine-grained sandstone, the Moab Sandstone Member, rests on the lower unit of the Entrada and is separated from it by a definite bedding plane. As this sandstone is traced southward, red beds appear below it and, near the south edge of Mancos Jim Butte (beyond the report area), these red beds have thickened and appear identical to Summerville strata which overlie the sandstone (R. H. Campbell, oral communication, 1957).

Thus, west and south of the mapped area, the Moab is intercalated in Summerville strata and becomes the Moab Tongue, whereas in the Moab and Abajo districts the Moab Sandstone Member forms the top of the Entrada Sandstone.

In the southern part of the area, the distinctive bedding planes that separate the Moab Sandstone Member of the Entrada Sandstone into narrow ledges easily distinguish it from the underlying, more massive unit of the Entrada Sandstone (fig. 7). As the Moab Sandstone Member is traced northward, the bedding planes decrease in number and become less distinct, and the sandstone becomes crossbedded. Near the head of Tuerto Canyon the member can no longer be recognized.

Lithologically the Moab Sandstone Member is similar in all respects to the underlying unit of the Entrada Sandstone.

The thickness of the Moab Sandstone Member seems to be relatively uniform. Near the south edge of the mapped area it is about 47 feet thick, and near the Causeway it is about 46 feet thick.

The contact of the Moab Sandstone Member with the overlying Summerville Formation is sharp; relief along the contact is slight, probably not exceeding 2 inches in a lateral distance of 100 feet. The contact is accentuated by the marked change from the very pale orange of the Moab Sandstone Member to the moderate reddish brown of the Summerville and by the change from a fine-grained sandstone to a shaly siltstone or very fine grained sandstone.

The intercalation of the Moab in Summerville strata, both north, west, and south of the Abajo Mountains, may represent former minor fluctuations in the shoreline of a newly advancing sea or it may reflect the continued rise of the ancestral high suggested by the rocks of Carmel time.

FIGURE 7.—Part of the east wall of Allen Canyon showing the general relations among the lower unit of the Entrada Sandstone (Jel), the Moab Sandstone Member (Jem), the Summerville Formation (Js), and the basal sandstone of the Morrison Formation (Jm).

SUMMERVILLE FORMATION

The uppermost formation of the San Rafael Group, the Summerville Formation, consists of pale reddish-brown (10*R* 5/4) to moderate reddish-brown (10*R* 4/6) shaly siltstone and very fine to fine-grained sandstone beds. In most places the Summerville closely resembles the overlying Salt Wash Member of the Morrison Formation, and commonly the two units form steep reddish-brown slopes above the pale-orange cliffs of the Entrada Sandstone. Where the Morrison has been removed, the Summerville forms a bench that caps the Entrada.

The Summerville, best exposed along the north, west, and southwest flanks of the Abajo Mountains, consists chiefly of alternating beds of shaly siltstone and fine-grained sandstone. The sandstone is more resistant and crops out as narrow ledges which give the slopes a steplike appearance.

Along the east valley wall of Harts Draw, a very pale orange (10*YR* 8/2) massive crossbedded friable fine-grained sandstone is about 40 feet above the basal contact of the Summerville. This sandstone, about 15 feet thick, normally forms a ledge, known as the mid-Summerville ledge, which is distinctive in the northern part of the area, but which cannot be traced southward beyond the head of Harts Draw. Only in the center and on the south flank of the mountains is the Summerville exposed as an uninterrupted sequence of reddish-brown beds.

One of the most distinctive units in the Summerville Formation is a lenticular bed of white to pale-red chert masses and nodules cemented by calcite. This chert bed has been arbitrarily selected as the uppermost unit of the Summerville. Where exposed, it is a lens 1 to 4 feet thick and about 10 feet long. In most places, however, the bed is concealed, and its trace is marked by angular nodules and fragments of chert which range in size from about 6 inches to about 4 feet. Locally these fragments are plentiful and form a somewhat continuous zone marked by oval-shaped masses of nodular chert.

This chert layer is in the Moab district (Baker, 1933, p. 51) to the north but not in the Elk Ridge area (R. Q. Lewis, Sr., oral communication, 1957) to the west. Possibly it continues to the south beyond the mapped area.

The following section of the Summerville Formation is along the east wall of Harts Draw.

Section of the Summerville Formation measured along the east wall of Harts Draw in NW¼ sec. 2, T. 33 S., R. 22 E.

	Ft	in
Jurassic:		
Morrison Formation.		
Summerville Formation:		
Chert, white, gray and pale-red, ledge-forming; locally contains calcite seams; disintegrates into angular nodules	1	5
Siltstone, light reddish-brown, shaly; forms gentle scree-covered slope	12	0
Sandstone, very pale orange, massive, cross-bedded, fine-grained; cliff former	17	0
Sandstone, reddish-brown, massive, fine-grained	4	0
Siltstone, reddish-brown, fissile, even-bedded; forms gentle scree-covered slopes	8	0
Sandstone, reddish-brown, platy, locally cross-bedded; thin, very pale-orange sandstone lenses intercalated	8	6
Siltstone, reddish-brown, platy, even-bedded; contains intercalated fine-grained sandstone lenses about 1 ft thick; forms gentle slope	22	0
Total Summerville Formation	72	11
Entrada Sandstone.		

In most places the Summerville Formation is about 85 feet thick, although it is locally as thin as 65 feet and as thick as 125 feet.

The contact of the Summerville with the overlying Salt Wash Member of the Morrison Formation has been arbitrarily selected, in the Abajo Mountains area, as the top of the nodular chert layer. In other areas, the Summerville-Salt Wash contact is at the base of the first "channeling" sandstone, so called because of the erosion channels at its base which reflect the stream-laid nature of the rocks. This contact was not used in the mapped area because of the lenticular nature of the sandstone. Where this sandstone is exposed, it generally is about 3 feet above the chert layer, although in places it is as much as 20 feet higher. If the first channeling sandstone is missing, about 60 feet of strata separate the chert layer from a channeling sandstone.

The Summerville Formation represents deposits laid down during the second major advance of the Carmel sea across this region. Whether the Entrada Sandstone was exposed to subaerial erosion before the area was inundated is uncertain. Baker (1933, p. 50) suggested, on the basis of outcrops in the Moab area, that small areas may have been exposed to weathering. No specific evidence to indicate such erosion was noted in the Abajo Mountains area, and it is suggested, therefore, that the seas advanced across unconsolidated dune sand, reworked it, and created a plain of almost no relief.

MORRISON FORMATION

In the Abajo Mountains area, the Morrison Formation of Late Jurassic age is divided into the Salt Wash Member, which consists of irregularly bedded light-gray to moderate grayish-yellow sandstone interstratified with pale-red claystone and siltstone and, overlying it, the Brush Basin Member, composed chiefly of variegated impure silty claystone and mudstone. These two units, together with the underlying Summerville Formation, form moderate to steep ledgy slopes between the sheer cliffs formed by both the underlying Entrada and the overlying Dakota Sandstone and Burro Canyon Formation. Outcrops of the Morrison Formation commonly are covered by dense foliage, talus, landslide blocks, and scree.

The Morrison Formation, the most widely exposed of the sedimentary units, crops out over broad areas in the north, west, and south parts of the mapped area. Although it is covered by younger strata on the east flanks of the mountains, it is well exposed farther east, beyond the limits of the mapped area, in the many canyons that dissect the Great Sage Plain. Uranium-vanadium deposits are localized in some beds in the Morrison Formation, and consequently it has been more thoroughly prospected than most of the units in the mapped area (p. 87).

Because of the heavy cover, it was not feasible to map the two members separately, so the Morrison is shown as a single undivided unit (pl. 1). In the field the major part of the Salt Wash Member can be recognized by the outcrops of its several intercalated sandstone beds, but it is difficult to locate the exact bed that separates the Salt Wash from the overlying Brushy Basin Member.

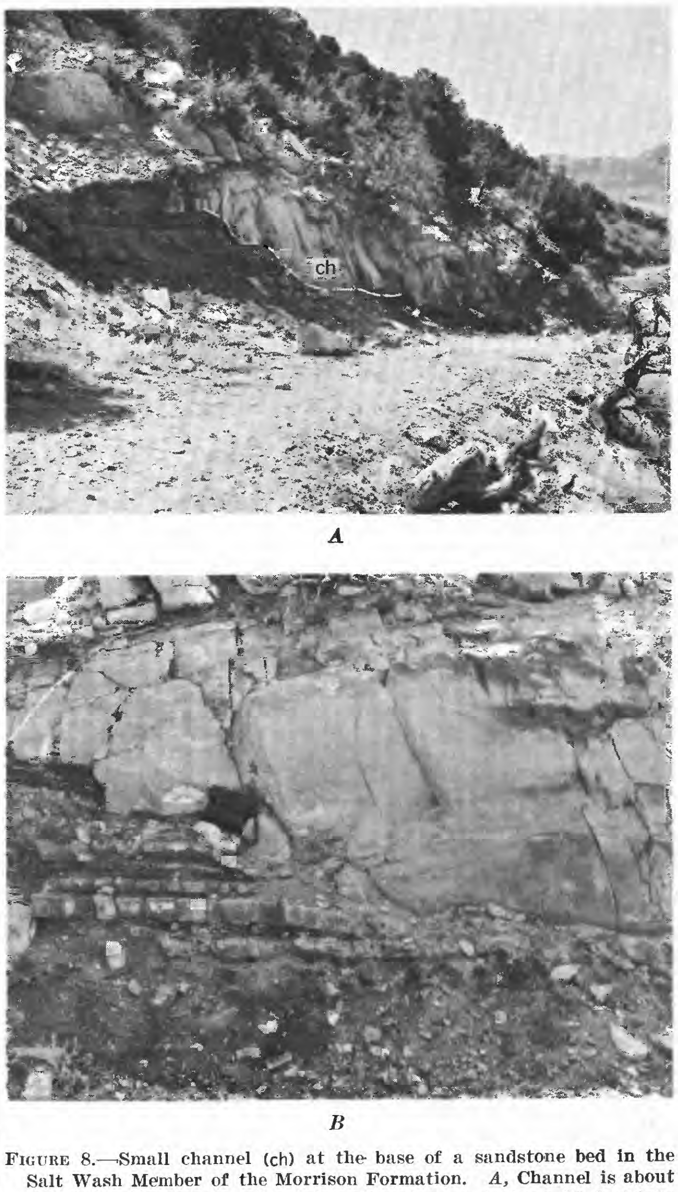
SALT WASH MEMBER

The Salt Wash Member of the Morrison Formation crops out as steep ledgy steplike slopes composed of lenticular sandstone beds that alternate at irregular intervals with beds of silty claystone, mudstone, and siltstone. The sandstone beds of the Salt Wash range from moderate grayish yellow (5*Y* 7/4) to light gray (*N*8). All are crossbedded and moderately friable; each ranges in thickness from 1 to 40 feet. In a few places, however, the intervening claystone beds become sandy, and a continuous sandstone sequence as much as 200 feet thick is formed.

Depressions of various sizes and shapes are at the base of most of the sandstone beds. These depressions, or channels, are fairly symmetrical in outline, are between 200 and 300 feet wide, and are cut 5 to 25 feet into the underlying mudstone and claystone (fig. 8*A*, *B*). In at least two localities (p. 96, 97), uranium-vanadium deposits are localized in the sedimentary rocks that fill these channels.

Commonly seven or eight sandstone beds are in the Salt Wash (fig. 9). Because these beds are not continuous laterally, they could not be correlated.

The sandstone is composed chiefly of fine (0.20 mm) to coarse (0.65 mm), angular to rounded frosted grains of quartz, plus small amounts of microcline and chert, all moderately to well cemented by calcite, silica, and iron oxide. Some of the quartz grains have quartz overgrowths. Scattered unevenly through the sandstone are stringers of conglomerate, claystone, and carbonaceous material. Pebbles in the conglomerate



A

B

FIGURE 8.—Small channel (ch) at the base of a sandstone bed in the Salt Wash Member of the Morrison Formation. *A*, Channel is about 160 feet wide and is estimated to have been cut about 15 feet into the underlying strata. *B*, Closeup showing the relations of the sandstone that fills the channel to adjacent variegated mudstone and siltstone.

are well rounded and are of quartz, quartzite, and chert. Silicified wood fragments are common, and many silicified logs, as much as 15 feet long and 2 feet in diameter, have been found in mines in the Salt Wash (fig. 28).

The claystone, mudstone, and siltstone beds that separate the massive sandstone are chiefly pale reddish brown (10*R* 5/4) but locally are altered to yellowish gray (5*Y* 7/2). Interbedded through the claystone and siltstone beds of the basal part of the Salt Wash are pale reddish-brown thin-bedded, very fine, fine-, and medium-grained sandstone beds that laterally grade into the claystone-siltstone sequence.

The following section of the Salt Wash Member is exposed in Harts Draw.

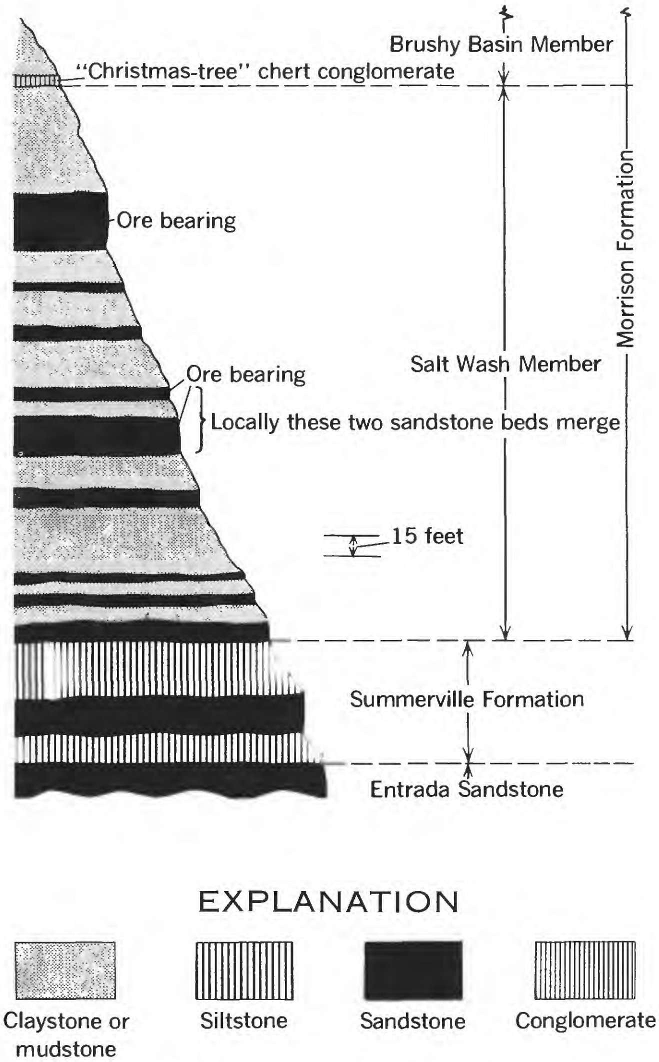


FIGURE 9.—Generalized section of the Salt Wash Member of the Morrison Formation showing the alternating sequence of sandstone, claystone, and mudstone beds.

Section of Salt Wash Member of Morrison Formation exposed on east valley wall of Harts Draw, NW¼ sec. 2, T. 33 S., R. 22 E.

Jurassic:
Morrison Formation:
Brushy Basin Member.
Salt Wash Member:

	Feet
Claystone and mudstone, alternating pale yellowish-gray and reddish-brown beds; forms gentle debris-covered slope	77
Sandstone, moderate grayish-yellow, friable, massive to platy, crossbedded, fine- to medium-grained; few well-rounded pebbles unevenly distributed; forms cliffs	36
Claystone and mudstone, pale-olive; frothy popcornlike surface; forms gentle slope	16
Sandstone, light-gray, massive, crossbedded, fine- to medium-grained	2
Claystone and mudstone, light-gray; frothy popcornlike surface; forms gentle slope	27
Sandstone, light-gray to moderate grayish-yellow, massive, crossbedded, fine- to medium-grained; forms cliffs	8
Claystone and mudstone, grayish-yellow-green, locally reddish-brown; popcornlike surface; weathers to gentle slope	35
Sandstone, light-gray to light-brown, massive, crossbedded, fine- to coarse-grained; well cemented by calcite; forms cliffs	8
Siltstone, claystone, pale reddish-brown; few intercalated sandstone lenses about 1 ft thick; forms gentle talus-covered slope	11
Sandstone, light-gray, massive, crossbedded, fine- to coarse-grained; firmly cemented by calcite; forms cliffs	21
Siltstone, pale reddish-brown, thin-bedded, fissile; forms gentle slopes	22
Sandstone, reddish-brown, massive, crossbedded, fine- to medium-grained; contains thin local siltstone lenses	11
Siltstone, reddish-brown, thin-bedded, fissile; contains few intercalated sandstone lenses about 3 ft thick	38
Sandstone, reddish-brown, crossbedded, fine- to medium-grained; pinches out laterally	2
Siltstone, pale reddish-brown, structureless; forms gentle slopes	7
Sandstone, reddish-brown, thick-bedded, crossbedded, fine- to medium-grained; forms steep slopes	7
Siltstone, reddish-brown, thin-bedded, fissile; forms gentle slopes	12
Sandstone, reddish-brown to light-brown, massive, crossbedded, fine- to medium-grained; forms cliffs	14
Siltstone, reddish-brown, thin-bedded, fissile; contains intercalated sandstone lenses about 1 ft thick; forms gentle slope	20
Total Salt Wash Member	374

Summerville Formation.

In the northern part of the area, the Salt Wash Member ranges in thickness from 250 to 400 feet. It thickens southward and near the south margin it is about 550 feet thick.

The contact of the Salt Wash Member with the overlying Brushy Basin Member was selected arbitrarily at the base of a fairly continuous conglomerate and conglomeratic sandstone, known locally as the "Christmas tree chert" (fig. 9).

The Salt Wash Member appears to have been deposited by northeast-flowing streams as a broad fan with its apex in south-central Utah and north-central Arizona (Craig and others, 1955, p. 135).

BRUSHY BASIN MEMBER

The Brushy Basin Member of the Morrison Formation consists chiefly of beds of impure structureless variegated claystone, mudstone, and siltstone. Generally these beds are a moderate greenish yellow (10*Y* 7/2), streaked irregularly here and there by pale red (10*R* 6/2), light red (5*R* 6/6), and light brownish gray (5*YR* 6/1). The unit crops out as moderate to steep slopes wherever the Salt Wash is exposed. The claystone beds, easily eroded, are intricately dissected into steep-walled gullies separated by narrow-crested divides. Landslide blocks are common; most are about 50 feet wide although a few are as much as 300 feet on a side.

The claystone beds, mostly structureless or very faintly crossbedded, have a frothy or popcornlike surface. They disintegrate into weakly cemented angular fragments and nodules that crumble easily and these form a thin veneer on the slopes. When wet, the claystone and mudstone beds become sticky and adhesive and are an effective barrier to travel.

Generally the claystone matrix consists of minute (0.01 mm and smaller) angular grains of quartz more or less tightly cemented by calcite and silica. Scattered irregularly through this matrix are angular to subround quartz grains that range from 0.05 to about 0.21 mm in diameter; most are about 0.1 mm. Also included is much bentonitic clay of volcanic origin.

The basal unit of the Brushy Basin Member is a pale yellowish-brown (10*YR* 6/2) conglomerate, the so-called Christmas tree chert. This unit contains many well-rounded red and green chert pebbles, most of which are about one-fourth inch in diameter, although some are as much as 2 inches. In a few places the conglomerate grades laterally into a conglomeratic or coarse-grained sandstone. The distinctive well-rounded red and green chert persists as sand grains, and the unit assumes an overall dark-gray hue.

The Brushy Basin Member in the Abajo Mountains area ranges in thickness from about 275 to 350 feet and has an average thickness of about 300 feet.

The contact of the Brushy Basin Member with the overlying Burro Canyon is sharp and undulatory and is marked by an abrupt change from a moderate greenish-yellow claystone to a very pale orange to light-tan conglomerate and conglomeratic sandstone. At the base of the conglomeratic sandstone are elongate shallow depressions that are filled by conglomerate lenses composed of well-rounded pebbles of quartz, quartzite, and chert and angular fragments of the greenish-yellow claystone. This contact has been described as an unconformity by many geologists (Gregory and Moore, 1931, p. 94; Baker, 1933, p. 54, and 1946, p. 91; Stokes, 1950, p. 93; L. C. Huff and F. G. Lesure, oral communication, 1955). Recent geologic work east of the La Sal Mountains, Utah, however, has suggested that the basal unit of the Burro Canyon Formation "* * * conformably overlies the variegated shale and mudstone units of the Brushy Basin Member of the Morrison Formation" (Carter, 1957, p. 308). The lack of good exposures of this controversial contact in the Abajo Mountains area prohibits any definite conclusion. The sharp lithologic change and the distinct depressions at the base of the Burro Canyon, however, suggest that the contact can best be described as a disconformity.

The Brushy Basin Member was derived chiefly from the same source area as the Salt Wash Member (Craig and others, 1955, p. 157).

CRETACEOUS SYSTEM

DAKOTA SANDSTONE AND BURRO CANYON FORMATION

Steep slopes formed on the variegated claystone and mudstone beds of the Brushy Basin Member of the Morrison Formation end at the base of a sheer vertical cliff composed of conglomerate, conglomeratic sandstone, sandstone, quartzite, claystone, and carbonaceous seams. These rocks, once assigned to the Dakota (?) Sandstone by Thorpe (1938b, p. 90), include two distinct formations—the Burro Canyon Formation of Early Cretaceous age at the base and the Dakota Sandstone of Late Cretaceous age at the top. In the present report, I also treat the two formations as a single unit, for poor exposures plus the vagueness and uncertainty of the contact between them make it almost impossible to discriminate between them in the Abajo Mountains area (fig. 10). The two units, therefore, are shown as one on the map (pl. 1).

These sandstone units form a cap rock that is well exposed on the northeast, east, and south flanks of the

A

B

FIGURE 10.—Mode of outcrop and general character of the Dakota and Burro Canyon. *A*, Steep cliff formed by the resistant Dakota and Burro Canyon (Kdb), undifferentiated, which caps the slopes formed on the weaker Brushy Basin Member of the Morrison Formation (Jmb). *B*, The coarse clastics that make up part of the Dakota and Burro Canyon.

mountains. The cap rock forms prominent irregular-surfaced broad benches around the base of the mountains, as well as the broad undulatory top of Shay Mountain, which can be traced southward along Shay Ridge to the north flank of Mount Linnaeus.

The Burro Canyon Formation, named by Stokes and Phoenix (1948) from exposures in western Colorado, has since been traced westward into southeastern Utah. Stokes and Phoenix excluded from the Burro Canyon all carbonaceous seams and sandstones that contain plant impressions; these units they relegated to the Dakota Sandstone.

In the Abajo Mountains area, the Burro Canyon Formation consists of alternating conglomerate, conglomeratic sandstone, and sandstone beds. The sandstone beds are light gray, and pale grayish-orange (10*YR* 8/4), friable, massive in places, and locally thin to thick bedded. All are crossbedded and channeled. Quartz is the dominant constituent; microcline and chert are present in small amounts. The grains range from 0.02 to 0.5 mm; most are about 0.1 mm in diameter. In shape they range from angular to well rounded; quartz overgrowths on a few of the quartz grains explain some of the angularity. Calcite is the dominant cement, and silica and iron oxide are subsidiary binding agents.

Conglomerate and conglomeratic sandstone are normally at the base, and the rocks become less coarse near the top. The pebbles in the conglomerate, grayish-white or various shades of gray, range from subround to well rounded, and from about half an inch to about 3 inches in diameter. Most are about 1 inch in diameter. Quartzite, chert, and quartz are dominant, and these are in a medium- to coarse-grained quartz sandstone matrix. Calcite is the chief cementing agent.

Scattered unevenly through the clastic rocks are thin distinctive moderate greenish-yellow (10*Y* 7/4) claystone lenses.

Lenticular beds of white to light-gray quartzite are characteristically intercalated in the uppermost strata of the Burro Canyon. East of the La Sal Mountains, a 1- to 8-foot-thick bed of white quartzite is the uppermost unit of the Burro Canyon (Carter, 1957, p. 308–309). This bed is present only locally in the Abajo Mountains area.

Some indication of the lithology of the Burro Canyon Formation is given by the following section measured along Shay Ridge.

Section of the Burro Canyon Formation along Shay Ridge measured in sec. 6, T. 34 S., R. 22 E. (unsurveyed)

	Feet
Cretaceous:	
Dakota Sandstone.	
Burro Canyon Formation:	
Conglomeratic sandstone, light-brown, massive, crossbedded; includes well-rounded pebbles of quartzite, quartz, and chert in a fine- to medium-grained sandstone matrix; grades laterally into sandstone facies	11
Claystone, light greenish-gray to light-gray, structureless; grades laterally into fine- to medium-grained sandstone	18
Sandstone, light-brown, massive, crossbedded, fine- to medium-grained; well cemented by calcite	20
Claystone, pale grayish-green, structureless	1
Sandstone, light-brown, massive, crossbedded, fine- to medium-grained; grades laterally into coarse conglomeratic sandstone	2
Total Burro Canyon Formation	52
Jurassic:	
Morrison Formation:	
Brushy Basin Member.	

Because the position of the upper contact of the Burro Canyon is not certainly known, the thickness of the formation in the Abajo Mountains area can only be estimated. Along Shay Ridge the Burro Canyon is about 50 feet thick; farther northeast I estimate it to be about 75 feet thick.

In areas adjacent to the Abajo Mountains, the Burro Canyon Formation is disconformably overlain by the Dakota Sandstone. This disconformity, a broad undulatory erosional plane, has been found to the northeast of the mapped area (Carter, 1957; G. W. Weir, oral communication, 1956) and to the east (L. C. Huff and F. G. Lesure, oral communication, 1957). In parts of these areas the uppermost unit of the Burro Canyon Formation is the 1- to 8-foot-thick light-gray quartzite (p. 28). Evidence of the disconformity includes shallow depressions in the top of the Burro Canyon and angular blocks of quartzite, identical to the light-gray quartzite, enclosed in the basal part of the Dakota Sandstone. Carter (1957, p. 311) interpreted these features to represent subaerial erosion of the Burro Canyon Formation and subsequent inclusion of the detritus in basal strata of the Dakota.

Locally in the Abajo Mountains area the disconformity is well marked by depressions and by angular quartzite boulders included in the basal part of the Dakota Sandstone, but for most of the report area the contact is concealed. Furthermore, several quartzite beds in the Burro Canyon might be confused with the uppermost quartzite. As a result, the criteria used in adjacent areas to locate the top of the Burro Canyon do not seem to be valid for the Abajo Mountains area.

The Dakota Sandstone is a pale grayish-orange (10*YR* 8/4) to yellowish-brown (10*YR* 7/4) massive, intricately crossbedded friable fine- to coarse-grained sandstone. In gross aspect the Dakota is a golden-brown sandstone differing slightly from the underlying Burro Canyon, which is generally grayish white.

Scattered irregularly through the Dakota are lenses of conglomerate, dark-gray claystone seams, lenticular carbonaceous seams, and, in a few places near the east margin of the mapped area, low-grade coal beds. In most places, the conglomerate, near the base of the Dakota, becomes less coarse near the top.

The basal conglomerate of the Dakota contains large angular to subround boulders of greenish-gray claystone, light-brown sandstone, and white quartzite scattered unevenly through its conglomeratic matrix. These boulders resemble some of the underlying strata in the Burro Canyon Formation and probably are detritus formed during a period of erosion prior to deposition of the Dakota (Carter, 1957, p. 311).

The sandstone consists chiefly of quartz grains of two sizes; most common are angular grains about 0.06 mm in diameter that surround large numbers of well-rounded quartz grains about 0.40 mm in diameter. Silica and calcite locally cement the sandstone firmly; elsewhere it is weakly cemented and friable.

Carbonaceous seams of irregular thickness and extent are widespread. Locally, these seams, as much as 2 feet thick, form a very low grade impure coal; in a few places they grade laterally into dark-gray distinctive claystone. Many of the thin sandstone beds have impressions of dicotyledon leaves along the bedding planes. In general, the Dakota is distinguished from the Burro Canyon by the leaf impressions, the carbonaceous seams, and the dark-gray shale.

The following section of the Dakota Sandstone is along Shay Ridge.

Section of the Dakota Sandstone measured along Shay Ridge in sec. 6, T. 34 S., R. 22 E. (unsurveyed)

Cretaceous:	
Mancos Shale.	
Dakota Sandstone:	*Feet*
Sandstone, pale grayish-orange, thin-bedded, platy, crossbedded; grades laterally into conglomeratic sandstone; much limonite stain	22
Shale, carbonaceous, dark-gray to black, fissile, finely laminated, lenticular; pinches out against light-brown fine- to medium-grained sandstone	8
Sandstone, yellowish-brown, massive, crossbedded, fine- to medium-grained; locally contains lenses of conglomerate; forms cliffs	13
Conglomerate and conglomeratic sandstone, pale grayish-orange, massive to thick-bedded, crossbedded; contains many large sandstone and quartzite boulders; in places contains stringers of fine- to medium-grained sandstone; well cemented; forms ledges	7
Total Dakota Sandstone	50
Burro Canyon Formation.	

The Dakota, over most of its area of outcrop, is about 50 feet thick, although it may thin to about 30 feet near its west limit. This westward thinning probably reflects a regional trend, for in the Great Sage Plain the Dakota also seems to thin as it is traced westward (L. C. Huff and F. G. Lesure, oral communication, 1957).

The contact of the Dakota Sandstone with the overlying Mancos Shale is conformable and consists of a gradational change from light yellow-brown sandstone to dark-gray sandstone, which in turn changes to the dark-gray to black shaly siltstone characteristic of the basal part of the Mancos Shale.

In this part of Utah, deposition during the Early Cretaceous was influenced by a slowly rising western highland. Eastward-flowing streams, heavily charged with detritus, deposited their loads as huge coalesced alluvial fans, which, upon consolidation, became the Burro Canyon Formation and the Dakota Sandstone. As these streams shifted back and forth, they cut new channels and filled old ones. This process, probably repeated many times, resulted in intersecting channels filled with coarse detritus and fossil plant matter. The carbonaceous seams and low-grade coal beds represent former backwater areas where there was a dense growth of vegetation. The fossil plant remains in the thin-bedded sandstone beds represent the large quantities of vegetation floated downstream. All the eastward-flowing streams eventually emptied into the Late Cretaceous Mancos sea, whose shoreline was slowly moving northward.

MANCOS SHALE

The Mancos Shale of Late Cretaceous age crops out chiefly along the east flank of the mountains where it is locally covered by pediment deposits. It is also exposed in the central part of the mountains where the beds, in places, have been folded to form broad shallow synclinal valleys.

The Mancos Shale is a dark-gray (*N* 3) to grayish-black (*N* 2) shaly fissile thin-bedded homogeneous siltstone. In a few places it has been baked and indurated, and its color altered to a light gray (*N* 7). Commonly it is soft and easily eroded and forms steep slopes covered by a thin scree of small angular chips.

Thin sandstone and limestone beds are interleaved irregularly through the formation. The sandstone commonly is dark gray (*N* 3) and relatively thick bedded and is composed of fine to medium grains of quartz. The limestone is light gray, thick bedded, and extremely fossiliferous and locally contains much sand. Throughout most of the mapped area, a fossiliferous sandy limestone bed, 2 to 4 feet thick, is 30 to 50 feet above the base of the Mancos. Near the east margin, however, this bed rests directly on the yellow-brown sandstone of the uppermost part of the Dakota. One of the most abundant fossils in this bed, as well as elsewhere in the Mancos, is a pelecypod *Gryphaea newberryi* (Stanton, 1893, pl. 5) that serves as an index fossil.

The maximum thickness of the Mancos Shale remnants preserved in the Abajo Mountains area is unknown, although it probably does not exceed 700 feet. It is about 250 feet thick near the Baker Ranger Station about 1 mile west of Monticello (Gregory, 1938, p. 62) and about 450 feet thick near Cooley Pass in the central part of the mountains.

To the east, near Cortez, Colo. (fig. 1), the full thickness of the Mancos is preserved beneath a thick cap of the Mesaverde Formation. It seems likely that the Mancos and the overlying Mesaverde once continued uninterrupted across the Abajo Mountains. Since that time, dissection has been extensive and only remnants of the basal part of the Mancos Shale are now left in the Abajo Mountains area.

The Mancos Shale represents deposits in the Mancos sea which gradually advanced northward across the area.

QUATERNARY SYSTEM

Five units of Quaternary age have been mapped: alluvium, dune sand, colluvium, rockslide and boulder-field deposits, and pediment deposits. Commonly these units are distinct and easily separated; in places, however, they merge and are distinguished only with difficulty.

ALLUVIUM

Alluvium covers most of the valley floors in the Abajo Mountains area. At the higher altitudes, the alluvium consists chiefly of poorly sorted angular gravel, cobbles, and boulders of both sedimentary and igneous rock derived from the valley sides. Bedrock crops out locally along the valley floors and the fill is, at the most, a thin veneer 1 to 5 feet thick. Downstream the alluvium thickens to as much as 40 feet and extends from one valley wall to the other. It supports an abundant vegetation that contrasts markedly with the sparse plant cover on the adjacent rocks and dune sand. At lower altitudes, where the streams debouch from the mountains, the alluvium shows a great diversity of materials. Streams that drain an area underlain by the dark-gray Mancos Shale deposit alluvium that is silty and dark gray; whereas sandy and reddish-brown to brown alluvium indicates a source area of Triassic and Jurassic rocks.

The resistant quartz diorite porphyry, one of the most common constituents of the alluvium, appears in all sizes and shapes. Large boulders and cobbles of the porphyry, common in the upper reaches of the stream valleys, decrease in number downstream. During periods of flood some of these large boulders and cobbles are moved considerable distances away from the mountains.

Near the north margin of the mapped area, the alluvial fill consists of well-sorted unconsolidated clay, silt, sand, and gravel. These sediments have been deposited in thin lenticular beds which locally interfinger and grade into one another. Along North Cottonwood Creek, Harts Draw, and Indian Creek, the alluvium is covered locally by unconsolidated dune sand that shifts back and forth with the wind and mixes with the alluvial fill.

Along the south and west margins of the area, the alluvial fill consists chiefly of angular to rounded pebbles, cobbles, and boulders of porphyry that form broad, easily traversed valley floors. For example, the bed of Johnson Creek consists of these coarse clastics, and the relatively even surface so formed can be traced almost to the head of the creek. About 1900, a wagon road to the Dream mine (p. 102) was constructed on part of the floor and many of the early prospectors and miners used this road as access to the mountains. Faint traces of it can still be seen where the stream cuts through the Johnson Creek dome.

DUNE SAND

Unconsolidated pale reddish-brown (10R 4/4) dune sand is exposed chiefly along the north and east margins of the mapped area. Deposits similar to these in adjacent areas have been called "eolian soil" (Cross, 1908), "loess" (L. C. Huff and F. G. Lesure, oral communication, 1957), and "surficial material of eolian origin" (G. W. Weir, oral communication 1957).

Commonly the dune sand forms broad irregular-shaped areas of low relief, as much as 2 miles wide that are locally stabilized by a thin to thick cover of vegetation. Near Harts Draw, for example, the dune sand is held in place by a sparse growth of sagebrush and greasewood. Here it ranges in thickness from 1 to 3 feet and conforms to the underlying topography. On the east margin of the mapped area, the dune sand overlies the pediment deposits and ranges in thickness from a thin film to as much as 10 feet. Where uncultivated, it supports a thick growth of pinyon pine and juniper. Over much of the eastern part of the area, however, farmers have cleared the forest and now cultivate pinto beans and wheat.

The dune sand is composed of angular to well-rounded quartz grains that range from 0.02 to 0.20 mm in diameter. All the grains are covered by a film of iron oxide that gives them a distinctive reddish-brown appearance. The iron oxide also acts as a weak cement, and many of the feebly held grains form aggregates as much as 0.4 mm in diameter.

During the violent windstorms, which are common in the spring and fall, the sand is blown about and sometimes blocks traffic along U.S. Highway 160 to Cortez, Colo., for short periods of time (fig. 1).

COLLUVIUM

Deposits mapped as colluvium are mostly an unsorted mixture of gravel, cobbles, boulders, and small landslide blocks, all jumbled together and all derived from strata that crop out on higher slopes. In general, these deposits conform to the underlying topography, but in a few places they are thick enough to form discrete irregular-shaped hummocks as much as 1 mile wide and 50 feet high. Examples of these hummocks are along the northwest-facing escarpment of Peters Point Ridge where they completely conceal the underlying formations. Here the colluvium was mapped; in most places, however, the colluvium forms only a thin veneer that incompletely conceals the underlying strata. In these places, the rocks were mapped as if the colluvial cover was nonexistent. Consequently, most of the formational contacts on plate 1 are dashed to reflect the uncertainty caused by the colluvial cover.

ROCKSLIDE AND BOULDER-FIELD DEPOSITS

Rockslides and boulder fields are principally on the crests and flanks of peaks underlain by the porphyry. Most of the fields have irregular outlines but a few are teardrop shaped, the apex pointing uphill. Some of the boulder fields that extend onto the broad floors of adjacent valleys show concentric ridges near their margins and are probably rock glaciers (fig. 11).

The rockslides consist of a jumble of loose angular boulders, all more or less tightly wedged together. Most of the boulders are about 2 feet long and about 3 inches thick, and all have sharp edges (fig. 11). In roadcuts, the boulders appear to have been pried loose from the bedrock (probably by frost action) and are nearly in place or only a short distance downslope.

Frost action probably is the dominant force in the formation of the fields. After the boulders are loosened, some movement occurs, either as a result of

FIGURE 11.—A rockslide and boulder field in the Abajo Mountains. Concentric ridges have formed near the toe of a large rockslide along the south flank of the South Peak laccolith.

oversteepening or because of slippage on ice that forms at the base of the slide (p. 106).

PEDIMENT DEPOSITS

On the north, east, and south, broad dissected pediments that slope away from the mountains are covered by unconsolidated, poorly sorted mixtures of angular to well-rounded sand, gravel, cobbles, and boulders (fig. 12). These deposits, mapped as pediment deposits (pl. 1), contain porphyry as the major constituent.

Although the pediment deposits are ill-sorted in detail, they have undergone some crude sorting in gross aspect. Thus, near the mountains, boulders as much as 5 feet on a side are common. Two to three miles from the mountains the sediments are less coarse and the maximum boulder is about 3 feet on a side (fig. 12). Six to eight miles from the mountains the pediment deposits are composed chiefly of well-rounded gravel and a few cobbles; individual boulders as much as 1 foot on a side are scarce.

The pediment deposits are as much as 100 feet thick near the mountains. This thickness decreases gradually to about 25 feet near the margins of the mapped area where the deposits are concealed locally by broad areas of dune sand.

The pediment deposits are absent from the Elk Ridge area to the west (R. Q. Lewis, Sr., oral communication, 1957). This absence suggests that both Elk Ridge and the Abajo Mountains were highlands, possibly united as a single topographic prominence, while streams stripped the sedimentary cover from the mountains, exposed the igneous core, and spread the resultant detritus far and wide across the adjacent lowlands.

FIGURE 12.—A pediment deposit near the Abajo Mountains showing the degree of sorting and size of debris. This exposure is about 3 miles east of the mountains.

IGNEOUS ROCKS

The major igneous rock exposed in the Abajo Mountains area is a quartz diorite porphyry (fig. 13*A*,*B*). It consists chiefly of euhedral phenocrysts of andesine, hornblende, and magnetite in a very dense light-gray aphanitic groundmass. In some specimens, distinct phenocrysts of quartz are widely and irregularly scattered through the groundmass (fig. 13*C*,*D*). Rocks properly classified as granodiorite porphyry (fig. 14) have been included in this group because they are not readily separable from the quartz diorite porphyry in the field.

A quartz diorite porphyry breccia, exposed only in the stocks, consists chiefly of angular to subrounded fragments of quartz diorite porphyry, plus minor amounts of sedimentary rocks, tightly cemented in a dark-gray aphanitic matrix (fig. 13*E*,*F*).

Small angular hornblendite inclusions, scattered irregularly through the igneous rocks, appear as olive-black crystalline masses about 2 inches on a side, firmly enclosed in, and in sharp contact with, the porphyry (fig. 13*G*,*H*). They consist chiefly of coarse grains of hornblende, magnetite, and plagioclase (labradorite) in a very fine grained groundmass.

QUARTZ DIORITE PORPHYRY

The quartz diorite porphyry exposed in the Abajo Mountains area is uniform in texture and appearance and is similar to much of the other porphyry found in the other laccolithic centers on the Colorado Plateau. Descriptions of these other porphyry have been published for the Henry (Hunt, 1953, p. 152), La Sal (Hunt, 1958, p. 319), Ute (Ekren and Houser, 1958, p. 75), and Carrizo Mountains (Emery, 1916) (pl. 3). Igneous rocks in these other laccolithic centers that are similar to those exposed in the Abajo Mountains area have been called diorite porphyry. For purposes of uniformity, the same name is used for the porphyry in the Abajo Mountains, but the "porphyry" in the Abajo Mountains is really best described as a hornblende dacite porphyry that locally grades into a hornblende rhyodacite porphyry.

The quartz diorite porphyry (fig. 13*A*) in the Abajo Mountains area ranges from light gray (*N* 7) to brownish gray (5*YR* 4/1). Scattered irregularly through an aphanitic groundmass are (a) blocky grayish-white plagioclase phenocrysts (andesine), (b) thin elongate black shiny needles and prisms of hornblende, and (c) black angular grains of magnetite (fig. 13*B*,*D*).

In some specimens, small bipyramidal grains of quartz are tightly cemented in the groundmass. Commonly these quartz grains are few in number and widely scattered.

The phenocrysts, of various sizes, are tightly embedded in an exceedingly fine grained groundmass of holocrystalline anhedral grains (fig. 13*A*,*B*) that makes up between 50 and 80 percent of the rock.

Plagioclase phenocrysts are the most common and are classed as andesine (An_{42}); they constitute about 30 percent of the rock. In general these phenocrysts range from about 0.3 mm to as much as 6.00 mm on a side, most of them being about 2.0 mm. In shape they range from euhedral to anhedral, but many have a crude rectangular outline and are subhedral. Albite twinning is common; Carlsbad-albite twinning is rare.

Many of the larger euhedral plagioclase phenocrysts are zoned. In the majority of these, the core is more calcic than the margins. Most of the cores are about An_{40}, but some are as calcic as An_{52} (labradorite). The margins have a soda-lime ratio of about $Ab_{72}An_{28}$, and fall, therefore, in the oligoclase range. In many of the thin sections studied, other grains of plagioclase have been tentatively identified as oligoclase (An_{25}) and labradorite (An_{52}). It is assumed that these oligoclase and labradorite grains represent either more sodic or more calcic parts of zoned crystals that were intersected by the plane of the thin section. In a few zoned phenocrysts, the center is less calcic (An_{40}) than the margins (An_{45}).

Inclusions of sphene and apatite are common in the plagioclase phenocrysts, and in a few thin sections hornblende crystals are enclosed by andesine.

Commonly the andesine phenocrysts are whole and but slightly fractured. Near the margins of the intrusions, however, the phenocrysts are shattered into angular fragments about 0.3 mm wide, which are separated from each other by the groundmass. Such fragmentation suggests that some of the phenocrysts were shattered prior to final consolidation of the magma, and the fragments then forced apart by the magma that filled the crevices.

The hornblende phenocrysts range from light green to dark green and constitute about 9 percent of the rock. All are strongly pleochroic and most appear as unfractured euhedral to subhedral prisms embedded in the very fine grained groundmass. Basal sections of rhombic outline are common and show the typical prismatic cleavage at angles of about 120° and 60°. The hornblende phenocrysts range from about 0.2 to 2.5 mm in length; most are about 0.5 mm long.

Magnetite appears as small opaque euhedral and subhedral phenocrysts, as dust in the groundmass, and as resorption residues in altered hornblende grains. The magnetite phenocrysts, which constitute about 3 percent of the rock, are about 0.1 mm wide, and have sharp angles and slightly ragged sides. The magnetite dust is scattered unevenly through the groundmass both as individual, somewhat rounded opaque specks and as small aggregates of particles about 0.02 mm in diameter. The resorption residues commonly appear as rounded opaque grains about 0.02 mm in diameter that form a dark fringe around the inside margins of altered hornblende grains. In places, the residue is almost dense enough to fill the entire cavity of the former hornblende crystal.

Sphene (titanite) appears both as individual euhedral wedge-shaped crystals about 0.2 mm long and 0.05 mm wide and as small clusters of three or four crystals.

Apatite is common and normally occurs either as subround grains about 0.1 mm in diameter embedded in the groundmass, or as small needlelike inclusions in the larger plagioclase or hornblende phenocrysts.

In addition to these minerals, which are common phenocrysts in most thin sections of unaltered rocks, a few thin sections contain minute grains of zircon and discrete anhedral grains of augite.

Sphene, apatite, zircon, and other minor accessory minerals constitute less than 1 percent of the rock.

The groundmass of the quartz diorite porphyry is dense, unbroken, and exceedingly fine grained, and commonly the grains are irregularly arranged to give a microgranular texture. Most of the grains in the groundmass are anhedral and from about 0.004 to about 0.008 mm in diameter. The groundmass includes, as essential constituents, quartz, potassium feldspar, plagioclase microlites (tentatively identified as oligoclase), and hornblende; and, as accessory minerals, magnetite dust and specks of apatite and sphene. Also included are such secondary components as opal, calcite, and sericite (?). Locally the plagioclase microlites are sufficiently well developed to give the section a felty texture.

As all the quartz diorite porphyries have fine-grained groundmasses, the exact mineralogic composition of these rocks is unknown. Consequently, chemical analyses of the rocks have been used to determine if any differences exist (table 3). In general, the rocks belong to the calc-alkalic series and are silica rich. Most of the hypabyssal rocks, although similar in appearance, differ somewhat in composition (table 3; fig. 14). Most of these rocks are properly classified either as granodiorite or as diorite and quartz diorite—rocks which, in essence, are very much alike. Of the analyzed rocks, six (Nos. 8, 10, 13, 14, 15, 17) are within the granodiorite field (fig. 14), five (Nos. 5, 7, 11, 12, 16) are diorite or quartz diorite, one (No. 6) is on the boundary line between the granodiorite-quartz diorite fields, and one (No. 9) falls squarely within the quartz monzonite field.

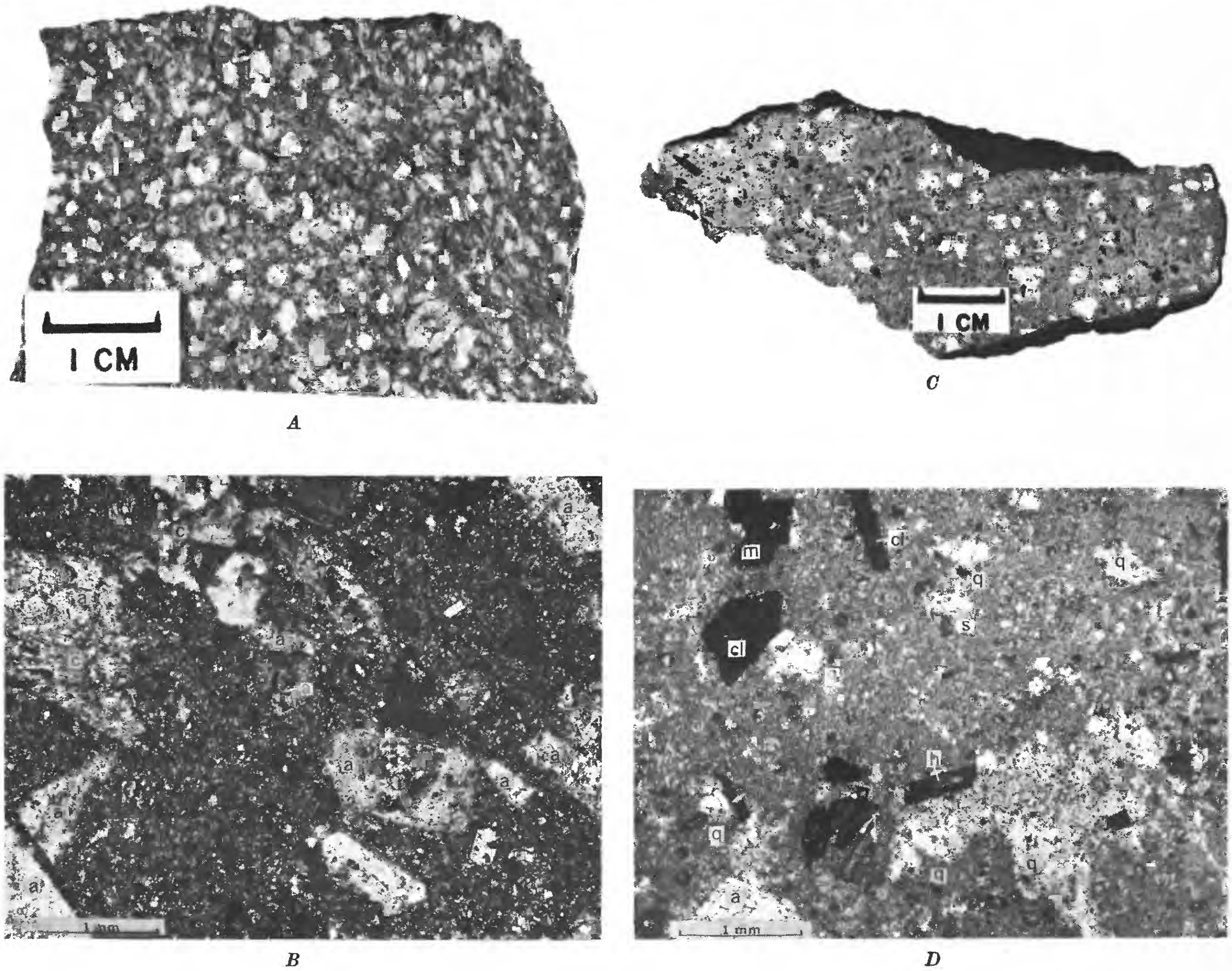
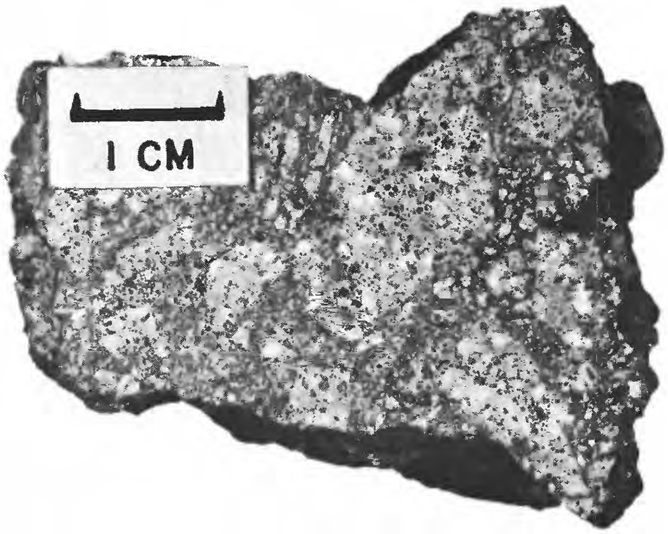
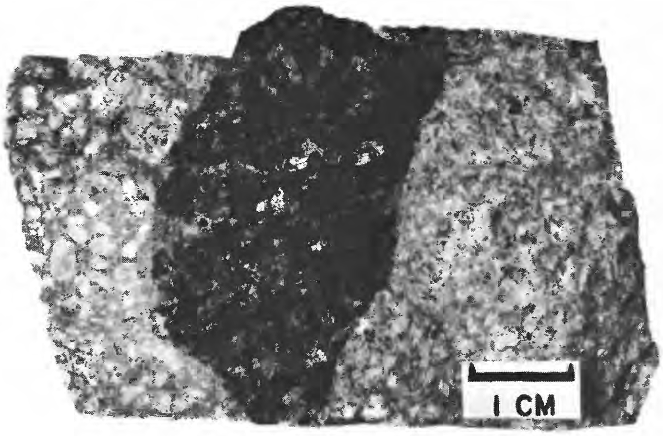


FIGURE 13.—Hand specimens and thin sections of igneous rock types exposed in the Abajo Mountains. All thin sections in plane

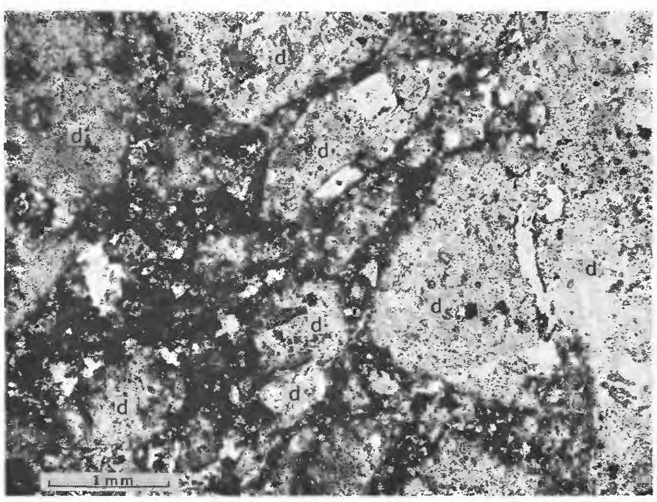
A, Hand specimen of quartz diorite porphyry, showing porphyritic texture. *B*, Thin section of same rock, showing fine-grained nature of the groundmass. *C*, Hand specimen of granodiorite phorphyry; note similarity to the quartz diorite porphyry. *D*, Thin section of granodiorite porphyry.



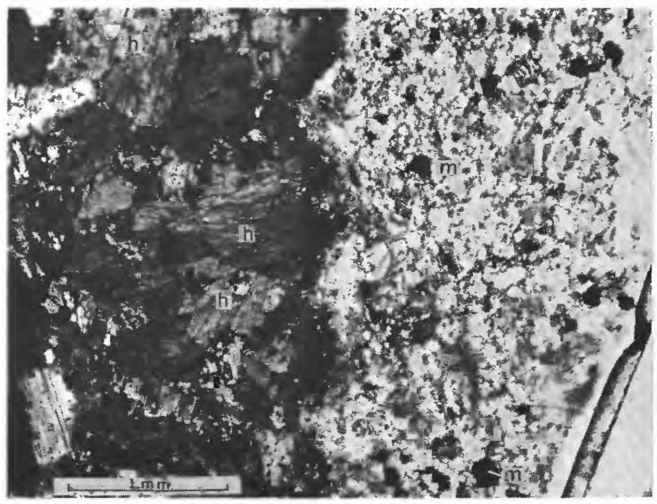
E



G



F



H

polarized light. d, quartz diorite porphyry; a, andesine; h, hornblende; m, magnetite; q, quartz; c, calcite; cl, chlorite; s, sphene.

E, Hand specimen of quartz diorite porphyry breccia from West Mountain stock; white angular fragments are quartz diorite porphyry. *F*, Thin section of quartz diorite porphyry breccia. *G*, Hand specimen showing inclusion of hornblendite in quartz diorite porphyry. *H*, Thin section showing contact of hornblendite and quartz diorite porphyry.

TABLE 3.—*Analyses, in percentages, of igneous rocks from the Abajo Mountains and a*

[Rapid rock analyses, except

	Stock rocks				Average of stock rocks	Hypabyssal rocks									
						Abajo Mountains									
	1	2	3	4		5*	6	7	8	9	10	11	12	13*	14
CIPW classification	I(II).4.2(3).4	I(II).5.1."4	I.4(5).1".4	I.4".1.2	I".4(5).1(2).3"	(I)II.4(5)."3.4	"II.4.3."4	I(II).4".3.4	I".4.2.4	I".4.2.3	I.4.2."4	(I)II.4".3.4	I(II).4"."3.4	I".4."2.'4	I".4."2."4
Laboratory No.	227799	152361	152364	152362	--------	A-107	227796	152363	152358	152360	152359	152356	152357	A-104	227795
Field No.	EMS-15-54	Wa-304	Wa-312a	Wa-305a	--------	Wa-101	EMS-12-54	Wa-309a	Wa-294	Wa-297b	Wa-297a	Wa-274	Wa-290a	Wa-52f	EMS-11-54
SiO_2	63.6	63.0	65.1	65.0	64.2	61.85	60.1	62.5	65.7	65.8	68.2	60.0	62.0	68.22	68.9
Al_2O_3	17.3	17.1	17.6	15.4	16.9	17.46	17.0	18.0	17.6	15.5	16.4	17.1	17.5	15.29	15.4
Fe_2O_3	1.2	3.9	2.9	2.8	2.7	1.88	2.6	1.5	1.7	1.5	1.6	2.8	3.0	.75	1.1
FeO	3.7	1.0	.7	.7	1.5	4.19	4.2	2.8	1.8	2.0	1.3	2.4	2.1	4.23	2.7
MgO	1.0	.8	.5	.6	.7	1.04	2.0	1.1	.7	.6	.5	1.8	1.5	.42	.6
CaO	3.2	.5	.7	.2	1.2	5.12	5.9	4.6	2.6	2.5	2.0	5.4	4.2	1.67	1.7
Na_2O	4.6	6.5	6.1	2.2	4.9	4.70	3.2	4.4	4.8	3.7	4.7	3.9	4.6	5.04	5.2
K_2O	2.2	4.8	4.0	9.7	5.2	2.17	2.3	2.1	3.2	4.8	3.5	2.2	2.1	3.96	3.8
TiO_2	.3	.5	.3	.4	.4	.45	.6	.4	.3	.3	.3	.6	.5	.20	.2
P_2O_5	.2	.2	.1	.1	.2	.29	.3	.2	.1	.1	.1	.3	.2	.18	.1
MnO	.1	.2	.1	.1	.1	.16	.2	.2	.2	.1	.1	.2	.2	.09	.1
H_2O[1]	2.2	1.1	1.3	1.1	1.6	.87	1.8	1.3	1.1	1.5	1.3	1.7	1.8	.44	.59
CO_2	1.4	.2	<.1	.1	.5	.07	.1	.2	.1	1.3	<.1	1.5	.8	.03	.41
Q	18.30	4.92	12.36	14.28	12.72	12.66	16.14	16.14	18.72	19.08	22.50	15.42	16.08	17.04	18.36
or	12.79	28.36	23.91	57.27	30.58	12.79	13.34	12.23	18.90	28.36	20.57	12.79	12.23	23.35	22.24
ab	38.77	55.02	51.35	18.34	41.39	39.82	27.25	37.20	40.35	31.44	39.82	33.01	38.77	42.44	44.01
an	15.01	1.67	2.78	.28	5.00	20.29	25.30	21.96	11.95	11.40	9.17	22.80	20.02	7.51	7.51
C	1.94	.61	2.14	1.22	1.33	--------	--------	.41	1.94	--------	1.53	--------	.41	--------	--------
di-en	--------	--------	--------	--------	--------	.50	.40	--------	--------	--------	--------	.60	--------	--------	--------
fs	--------	--------	--------	--------	--------	.92	.53	--------	--------	--------	--------	.26	--------	--------	--------
wo	--------	--------	--------	--------	--------	1.39	.93	--------	--------	--------	--------	.93	--------	--------	--------
hy-en	2.50	2.00	1.30	1.50	1.80	2.10	4.60	2.80	1.80	1.50	1.30	3.90	3.80	1.00	1.50
fs	5.28	--------	--------	--------	--------	4.62	4.36	3.70	1.72	2.11	.66	1.06	.92	6.73	3.83
mt	1.86	5.57	1.62	1.39	3.94	2.78	3.71	2.09	2.55	2.09	2.32	4.18	4.41	1.16	1.62
ap	.34	.34	.34	.34	.34	.67	.67	.34	.34	.34	.34	.67	.34	.34	.34
il	.61	.91	.61	.76	.76	.91	1.22	.76	.61	.61	.61	1.22	.91	.46	.46
hm	--------	2.08	1.76	1.92	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

[1] Reported as total H_2O, except where marked by †, which symbol denotes H_2O+.

1. Altered quartz diorite porphyry from East Mountain stock. (Collected by E. M. Shoemaker.) Analysts: P. L. D. Elmore and K. E. White.
2. Granodiorite porphyry breccia from East Mountain stock, unfractured. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
3. Granodiorite porphyry from East Mountain stock, partly fractured. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
4. Altered granodiorite porphyry from East Mountain stock, fractured. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
5. Quartz dicrite porphyry, Horsehead laccolith. Analyst: J. L. Theobald.
6. Quartz diorite porphyry, Jackson Ridge laccolith. (Collected by E. M. Shoemaker.) Analysts: P. L. D. Elmore and K. E. White.
7. Quartz diorite porphyry, South Peak laccolith. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
8. Granodiorite porphyry, South Peak laccolith. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
9. Quartz monzonite porphyry, roof of concealed unnamed laccolith; at contact with Morrison Formation in Cooley Gulch at Dixon's mine. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
10. Granodiorite porphyry, roof of concealed unnamed laccolith; about 25 feet from sample 9. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
11. Quartz diorite porphyry, Scrub Oak laccolith. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
12. Quartz diorite porphyry, Porcupine laccolith. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.

comparison with analyses of similar rocks in the Henry, La Sal, Ute, and Carrizo Mountains

where noted by an asterisk (*)]

			Average of hypabyssal rocks	Miscellaneous												
				Henry Mts.	La Sal Mts.	Ute Mts.	Carrizo Mts.	Averages of samples from different localities								
15	16*	17*		18*	19*	20*	21*	22*	23*	24*	25*	26*	27*	28*	29*	30*
"II.4".3.3	II.4".3.4	(I)II.4(5).2(3)."4	I(II).4".(2)3."4	I".4(5)."3.4	I".(4)5.(1)2.4(5)	II.(4)5.3.4	(I)II.4".2(3).4	II.(4)5.3.4	II(III).5.3".4	(I)II.4".3.4	II."5.3".4"	(I)II.4.3.4	I(II).4.(2)3.4	(I)II.4.3.4"	II.4.3.4	"II.4.3.4
152355	A-106	A-103	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Wa-272	Wa-104a	Wa-91a	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Oxides																
58.8	58.05	60.87	63.15	62.41	66.24	57.2	63.18	56.77	51.86	59.59	54.20	61.12	65.68	63.6	61.6	66.2
17.1	16.74	16.37	16.72	18.29	16.95	17.0	16.47	16.67	16.40	17.31	17.17	17.65	16.25	16.7	16.2	15.6
2.6	.46	2.26	1.82	2.07	1.72	2.9	2.36	3.16	2.73	3.33	3.48	2.89	2.38	2.2	2.5	1.4
3.8	7.50	4.13	3.32	1.91	.80	4.1	2.28	4.40	6.97	3.13	5.49	2.40	1.90	3.0	3.8	3.4
1.8	1.56	1.41	1.16	1.05	.83	2.9	1.33	4.17	6.12	2.75	4.36	2.44	1.41	2.1	2.8	1.9
5.2	5.34	4.36	3.89	4.75	2.88	5.9	4.77	6.74	8.40	5.80	7.92	5.80	3.46	5.5	5.4	4.7
2.9	3.72	4.28	4.24	5.29	7.51	4.1	4.40	3.39	3.36	3.58	3.67	3.83	3.97	4.0	3.4	3.9
3.5	1.49	3.30	2.95	2.01	1.99	2.1	2.93	2.04	1.33	2.04	1.11	1.72	2.67	1.4	2.1	1.4
.6	.50	.47	.42	.35	.32	.7	.66	.84	1.50	.77	1.31	.42	.57	.6	.7	.6
.3	.39	.34	.22	.18	.17	.3	.28	.25	.35	.26	.28	.15	.15	.2	.3	.2
.2	.15	.13	.15	.09	.05	.1	.15	.13	.18	.18	.15	.15	.06	.1	.1	.1
1.7	2.93	1.26	1.41	1.14	.33	2.6	.87	1.36	.80†	1.26	.86†	1.43	1.50	.56†	1.22	.69†
1.4	2.01	1.15	.71	---	.65	.3	---	---	---	---	---	---	---	---	---	---
Norms																
13.68	12.18	11.28	15.60	12.72	9.42	8.58	15.48	9.12	---	14.76	5.34	16.50	22.32	19.62	17.64	24.18
20.57	8.90	19.46	17.79	11.68	11.68	12.23	17.24	11.68	7.78	11.68	6.67	10.01	16.12	8.34	12.23	8.34
24.63	31.44	36.15	35.63	44.54	63.40	34.58	37.20	28.82	28.82	30.39	31.44	31.96	34.06	34.06	28.82	33.01
23.35	23.91	15.85	17.79	20.29	6.95	21.96	16.68	24.46	25.58	25.30	26.97	26.41	16.68	23.35	22.80	20.85
---	.20	---	---	---	---	---	---	---	---	---	---	---	.61	---	---	---
.20	---	.80	.10	.60	2.10	1.40	1.60	2.00	3.50	.60	2.80	.50	---	.80	6.00	4.00
.13	---	1.06	.26	.40	---	.79	.53	.79	1.85	.13	.66	.13	---	.40	.26	.26
.35	---	1.86	.35	1.04	2.78	2.32	2.32	3.02	5.68	.81	4.41	.58	---	1.28	.93	.70
4.30	3.90	2.70	2.80	2.00	---	5.90	.40	8.40	11.80	6.30	8.10	5.60	3.50	4.50	6.40	4.10
4.09	12.94	3.96	4.09	1.06	---	2.90	2.51	3.43	6.60	1.85	4.75	1.58	.82	2.38	3.56	3.83
3.71	.70	3.25	2.55	3.02	1.86	4.18	3.48	4.64	3.94	3.36	5.10	4.18	3.48	3.25	3.71	2.09
.67	1.01	.67	.34	.34	.34	.67	.67	.67	1.01	.67	.67	.34	.34	.34	.67	.34
1.22	.91	.91	.76	.61	.61	1.37	1.37	1.52	2.89	1.52	2.43	.76	1.22	1.22	1.37	1.22
---	---	---	---	---	.48	---	---	---	---	---	---	---	---	---	---	---

13. Grandiorite porphyry(?), Viewpoint laccolith. Analyst: J. L. Theobald.
14. Granodiorite porphyry(?), Viewpoint laccolith. (Collected by E. M. Shoemaker.) Analysts: P. L. D. Elmore and K. E. White.
15. Granodiorite porphyry from dike attached to Scrub Oak laccolith. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. H. Thomas.
16. Quartz diorite porphyry. Sill in Mancos Shale exposed near head of Indian Creek. Analyst: J. L. Theobald.
17. Granodiorite porphyry. Dike along east flank of Shay Mountain. Analyst: J. L. Theobald.
18. Diorite porphyry, Henry Mountains, Utah; average of 10 analyses (Hunt, 1953).
19. Albitized diorite porphyries, La Sal Mountains, Utah; average of two analyses (one altered rock) (C. B. Hunt, oral communication).
20. Diorite porphyry, Ute Mountains; average of four analyses (F. N. Houser, oral communication).
21. Diorite porphyry, Carrizo Mountains, one analysis (Emery, 1916).
22. Diorite (excluding quartz diorites); average of 70 analyses (Daly, 1933, p. 16).
23. Diorite; average of 50 analyses (Nockolds, 1954, p. 1019).
24. Andesite; average of 87 analyses (Daly, 1933, p. 16).
25. Andesite; average of 49 analyses (Nockolds, 1954, p. 1019).
26. Hornblende andesite; average of 24 analyses (Daly, 1933, p. 16).
27. Dacite; average of 90 analyses (Daly, 1933, p. 15).
28. Dacite; average of 50 analyses (Nockolds, 1954, p. 1015).
29. Quartz diorite; average of 55 analyses (Daly, 1933, p. 15).
30. Tonalite; average of 58 analyses (Nockolds, 1954, p. 1015).

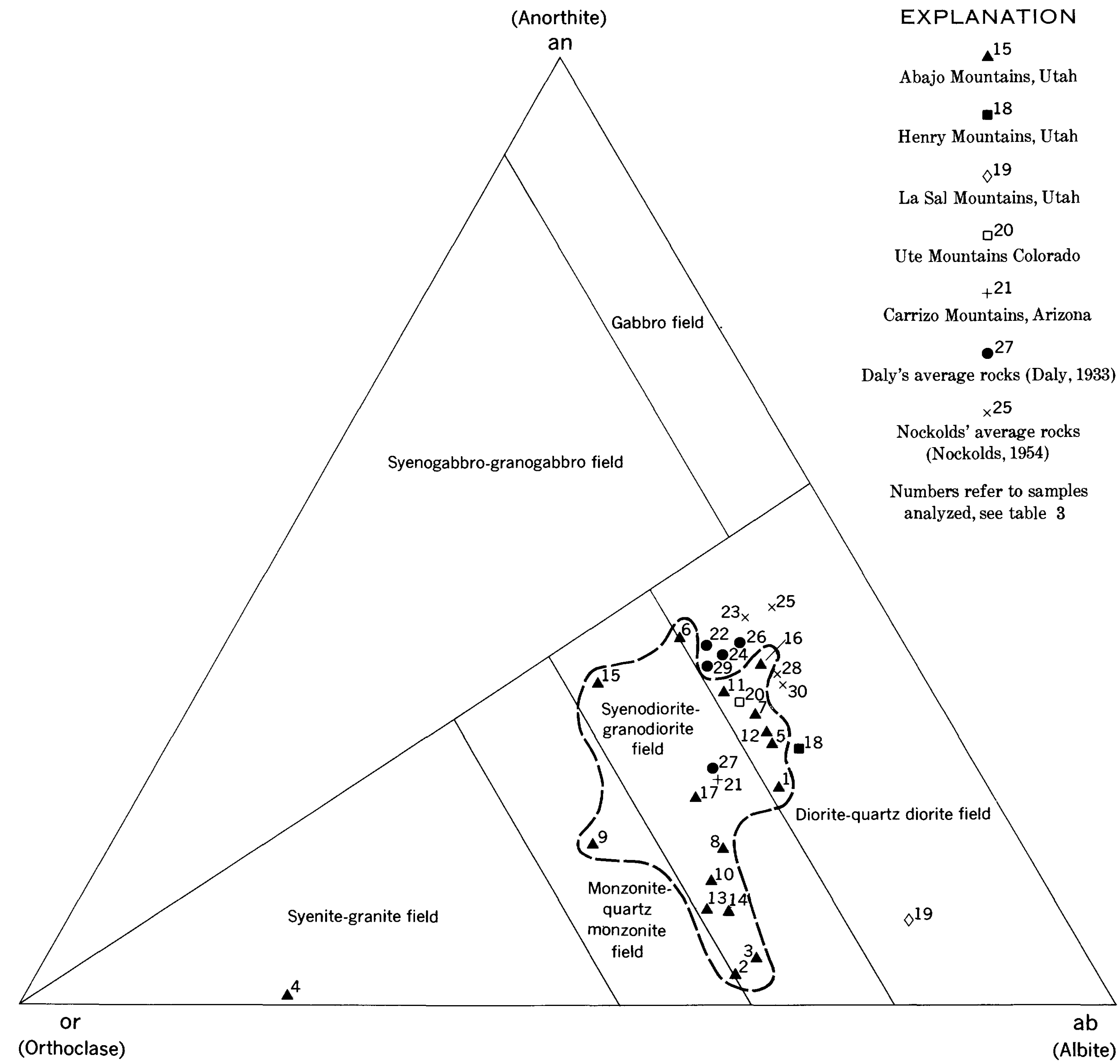


FIGURE 14.—Plot of normative feldspar (or, ab, and an) relations for the igneous rocks of the Abajo, Henry, La Sal, Ute, and Carrizo Mountains. (Fields in the ternary diagram were established by W. R. Jones and Walden Pratt, on the basis of data from Nockolds' (1954) calc-alkaline series).

Sample(s)	Rock		Analyses, average of—	Reference
	Type	Location		
1-4	Stocks of quartz diorite porphyry, granodiorite porphyry, and altered granodiorite porphyry.	Abajo Mountains, Utah		
5-14	Laccoliths of quartz diorite porphyry, and granodiorite porphyry	do		
15, 17	Dikes of granodiorite porphyry	do		
16	Sill of quartz diorite porphyry	do		
18	Diorite porphyry	Henry Mountains, Utah	10	Hunt (1953, p. 154).
19	do	La Sal Mountains, Utah	2	Hunt (1958, p. 321).
20	do	Ute Mountains, Colo.	4	E. B. Ekren and F. N. Houser (oral communication, 1959).
21	do	Carrizo Mountains, Ariz.	1	Emery (1916, p. 358).
22	Diorite		50	Daly (1933, p. 16).
23	do		50	Nockolds (1954, p. 1019).
24	Andesite		87	Daly (1933, p. 16).
25	do		49	Nockolds (1954, p. 1019).
26	Hornblende andesite		24	Daly (1933, p. 16).
27	Dacite		90	Do.
28	do		50	Nockolds (1954, p. 1015).
29	Quartz diorite		55	Daly (1933, p. 15).
30	Tonalite		58	Nockolds (1954, p. 1015).

I interpret these rock analyses to mean that the rocks were formed during the initial stages of normal magmatic differentiation and plutonic crystallization. The process was halted before the magma could differentiate completely. As a result one dominant rock type was formed, rather than several distinct and widely disparate types such as one might expect had differentiation continued to its ultimate end. This normal differentiation is shown by a silica-variation diagram (fig. 15*B*) on which the analyzed rocks have been plotted; as the lime decreases, the silica, potassium oxide, and sodium oxide increase.

The porphyritic texture of the hypabyssal rocks suggests that the silica-lime variation may be explained, at least in part, in another way. Modal analyses indicate that in some rocks as much as 78 percent of their volume is groundmass, the phenocrysts (andesine, hornblende, magnetite) accounting for only 22 percent (fig. 15, No. 13). Conversely, in other rocks only 53 percent of their volume is groundmass, the phenocrysts accounting for as much as 47 percent, (fig. 15, No. 16). Because much of the silica, potassium oxide, and possibly sodium oxide is in the groundmass, the rocks having a high proportion of groundmass may be unusually rich in silica, potassium oxide, and sodium oxide, and poor in lime. By contrast, rocks with a high proportion of phenocrysts may have a high lime content (for more andesine phenocrysts are present) and a low content of silica, potassium oxide, and sodium oxide (for less groundmass is available).

The phenocryst-groundmass ratios of 10 rocks, for which chemical analyses have been completed, are plotted in figure 15*A*. Of these 10, 8 (Nos. 5, 7, 9, 10, 11, 13, 15, 16), and possibly 9 (No. 12), fall into a pattern which implies that the chemical composition of rocks may be related, in part, to the ratio of groundmass to phenocrysts. One of these rocks (No. 8) deviates markedly from the pattern.

Locally the stock rocks have been drastically altered (fig. 14, sample 4). Some of the alteration may have been deuteric, but most of it seems to have been hydrothermal and to have taken place after the stocks were consolidated and fractured. This relation of fractures to alteration is brought out in table 3 and figure 14. Samples 1 and 2 are of somewhat fractured quartz diorite and granodiorite porphyries. Sample 3 is more fractured, and sample 4 is thoroughly fractured—and intensely altered.

I suggest that the hydrothermal solutions required for the alteration were squeezed out of the parent magma as it underwent final crystallization. During this last convulsive movement, the stocks were probably fractured, and the solutions, under great pressure, moved into, up, and along the newly formed fractures. During their ascent, the liquids precipitated small amounts of sulfides in the host rock near the fractures and simultaneously altered the host rocks, and, as a final stage, deposited silica in the fractures. By far the greater number of sulfide deposits in the Abajo Mountains are in and near these fracture zones in the stocks (p. 101).

Almost every mineral in the stock rocks has been severely altered and changed to a more stable form. Most of the hornblende has been completely altered to chlorite (penninite) and calcite. Every feldspar phenocryst is changed—some have been completely altered to sericite and calcite which still preserve the phenocryst outline; others are rimmed by sericite and calcite, and still others contain irregular and elongate blebs of these alteration products. Much of the magnetite has been altered to a brown hydrated iron oxide (limonite), but, locally, some unaltered(?) magnetite is scattered through the groundmass. In general, the groundmass is only partly altered, but it is stained brown by disseminated iron oxide.

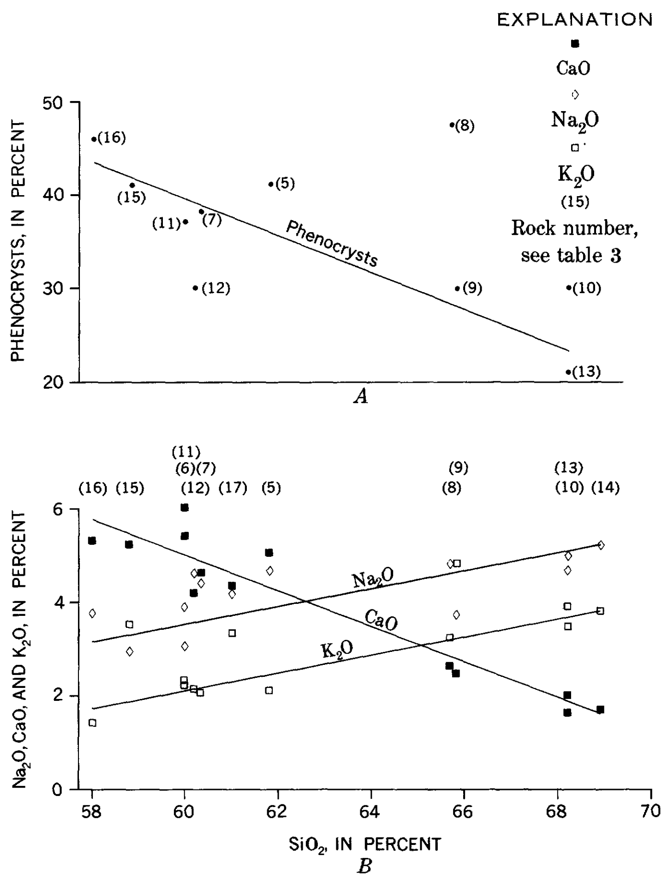


FIGURE 15.—Silica-variation diagram of hypabyssal rocks from the Abajo Mountains, showing the relation of phenocryst content (A) to the sodium oxide, lime, and potassium oxide contents (B).

Rock alteration, however, is not confined to the stocks. Much of the quartz diorite porphyry of the laccoliths has been altered, and a gradational sequence exists from practically unaltered rocks to those that have been partly altered. In the partly altered rocks, the greatest change has occurred in the hornblende and plagioclase phenocrysts. Commonly the hornblende phenocrysts are almost completely changed, the plagioclase phenocrysts are moderately changed, and the magnetite phenocrysts are changed little or not at all. The groundmass is unaltered, or altered very slightly.

The hornblende phenocrysts generally have been replaced by chlorite (penninite), magnetite dust (resorption residues), a presumably hydrated iron oxide, and calcite. The outline of the phenocrysts has been preserved in the groundmass, and the space so provided is filled by alteration products.

The altered plagioclase phenocrysts have rounded edges, embayed areas, and patches of irregular outline and shape in the phenocryst centers. These irregular patches are filled with sericite, opal, small amounts of calcite, and kaolin(?). In the zoned phenocrysts, the alteration is along the zone margins, and here the major replacement minerals are fine-grained feldspar and sercite.

In general, the magnetite grains have not been altered, for in most samples examined, good euhedral crystals of magnetite are common.

I suggest that most of the rock alteration in the laccoliths is of deuteric origin, caused by residual liquids entrapped in the magma. Because only small amounts of such liquids were involved, the rock alteration is localized and not severe. Support for this view is the small and insignificant sulfide deposits formed near the laccoliths which mirror this paucity of residual fluids.

QUARTZ DIORITE PORPHYRY BRECCIA

In and near the East and the West Mountain stocks is an unusual breccia, here called the quartz diorite porphyry breccia. The breccia crops out as irregular-shaped masses, and consists of angular fragments of quartz diorite porphyry, blocks of sedimentary rocks, and inclusions of hornblendite. All are chaotically jumbled, and all tightly held in an aphanitic matrix somewhat similar in composition to that of the porphyry itself.

The breccia weathers to form large blocky irregular areas marked by steep slopes and rocky ledges. Generally a veneer of loose angular boulders mantles such slopes, and the brecciated areas, therefore, are almost free of vegetation. The margins of these brecciated patches are vague and irregular, and in most places there is a gradational transition from a brecciated zone to unfractured porphyry. As far as can be determined, the breccia grades into the undisturbed porphyry that forms the dikes, sills, bosses, and apophyses injected into the shatter zone. The contact between the breccia and the adjacent sedimentary rocks is also transitional.

The breccia is pale olive (10*Y* 6/2) that locally darkens to medium gray (*N* 5). In a few places, the breccia, cut by a plexus of minor fractures, is altered to dark yellowish orange (10*YR* 6/6)or moderate reddish brown (10*R* 4/6).

The breccia consists of a jumble of angular to subround fragments that range from ⅛ to 6 inches in length, most being about ½ inch long. The smaller fragments commonly are angular and have an irregular outline. In contrast, most of the larger fragments are rectangular and blocky and have slightly rounded corners.

On the basis of color alone, three distinct types of quartz diorite porphyry fragments can be recognized in the breccia. Most common are bluish white (5*B* 9/1), the next are medium bluish gray (5*B* 5/1), and the least common are dark gray (*N* 3). All fragments, no matter what their color, seem to contain the same minerals but have differing ratios of light to dark constituents. Further, all porphyry fragments, again regardless of color, display a variety of textures ranging from some that are very fine grained to others that are coarse grained and in which the individual grains can be seen by the unaided eye. Some porphyry inclusions have been badly deformed. In these the minerals have been stretched, elongated, and alined to give a gneissic texture.

The sedimentary fragments enclosed in the breccia make up less than 5 percent of the whole. Only two sedimentary units seem to be represented on the basis of the fragments found—the Mancos Shale and the Morrison Formation. These fragments are only slightly altered, and retain much of their original appearance.

The hornblendite fragments are identical to similar inclusions in the undeformed quartz diorite porphyry. Normally they are olive black (5*Y* 2/1), about 2 inches in length, coarse grained, and apparently scattered at random through the breccia.

HORNBLENDITE INCLUSIONS

Hornblendite inclusions, scattered irregularly through the porphyry, have been found in every intrusive body in the area, whether a small dike or the core of a stock. These inclusions are olive black (5*Y*

2/1) to olive gray (5*Y* 4/1), angular to subround, massive, granular fragments tightly enclosed in the porphyry. Most are oblong, about 2 by 1 by ½ inch in size. Commonly they are in sharp and well-defined contact with the surrounding rocks (fig. 13,*G*), although a few show a faint gradational border.

The hornblendite fragments consist of a tight intergrown mesh of hornblende crystals, anhedral grains of plagioclase feldspar (labradorite, An_{55}), magnetite (and other iron oxides), and small amounts of minor accessory minerals, chiefly apatite. In all the inclusions examined, the texture of the hornblendite remained the same from margin to core. No reaction rims were present. In thin section the edges of the fragments appeared slightly frayed, and the unchanged groundmass of the porphyry filled the embayed areas.

Most of the inclusions observed were massive and the grains showed no alinement. In a few, however, the hornblende and plagioclase grains were alined to give the fragment a gneissic appearance.

Some of the hornblendite fragments contain little but hornblende; in these, hornblende makes up about 70 percent by volume, plagioclase feldspar about 5 percent, and iron oxides about 10 percent. The remaining 15 percent consists of a microcryptocrystalline groundmass and small grains of titanite and apatite. In other fragments, especially those with gneissic texture, the plagioclase is more plentiful. In these, labradorite (An_{55}) constitutes about 40 percent of the volume, hornblende about 55 percent, and magnetite and apatite the remaining 5 percent.

Optically the hornblendes are similar to those in the porphyry, although they differ in size, those in the inclusions being as large as 3.0 mm. In the inclusions, however, the hornblendes are almost unaltered, in contrast to those in the stock and laccolithic rocks that are either wholly or partly altered.

The labradorite grains range from subhedral to anhedral, and are about 0.6 mm in diameter. None are zoned, in marked contrast to these plagioclase grains in the porphyry. A few labradorite grains are rimmed with alteration products such as sericite, cryptocrystalline quartz, and calcite, but most of the labradorite grains are practically unaltered.

The general absence of alteration in the inclusions contrasts with the intense alteration of the stock rocks (p. 39) and with the moderate and localized alteration of the laccolithic rocks. This lack of alteration of the inclusions suggests that they are xenoliths plucked from a basement complex, rather than autoliths formed during the crystallization of the parent magma. The inclusions have been interpreted differently by A. C. Waters and C. B. Hunt (*in* Hunt, 1958, p. 352), who have suggested that the hornblendite fragments represent "refractory remnants" of an extensive metamorphic sequence that underwent palingenesis. (The resultant parent magma domed the sedimentary rocks and formed the laccolithic mountains.) The remnants were not incorporated into the liquid magma, but were altered sufficiently to remain in equilibrium with the magma.

STRUCTURAL GEOLOGY

Two types of structural features can be recognized on the Colorado Plateau, (a) those due to tectonic activity and which now appear as folded and faulted features composed of sedimentary rocks and (b) those formed as a result of igneous intrusion. In the first category are such diverse units as the Monument upwarp, the San Rafael swell, and the Paradox fold and fault system. The second category includes the laccolithic mountain groups.

Hunt (1956, p. 43, 45, 73) has suggested that the two types of structural features were formed independently and are not related. His view, however, has been challenged by Kelley (1955, 1956) who saw a distinct relation between the two types.

Structural trends in and near the Colorado Plateau suggest that the plateau has undergone at least three separate and independent orogenies—the first in the Precambrian, a second in the Pennsylvanian and Permian, and a third during Laramide time. The Precambrian tectonic features trend northeastward (Kelley, 1955, p. 20). In contrast, the structural features of Permian and Pennsylvanian age (the Paradox basin and the Zuni uplift) trend northwestward, and the youngest set of features (the Monument upwarp and the Defiance uplift), of Laramide age, trend northward. Kelley, impressed by the northwest pattern, pictured the plateau as having been divided unequally by several lineaments into northwestward-trending segments. All the laccolithic centers are in one such segment, the San Juan segment, which is bounded on the north by the Uncompahgre lineament and on the south by the Zuni lineament (Kelley, 1955, p. 59). Kelley suggested that these centers, despite their apparent lack of alinement, fit the regional pattern in that they are alined parallel to the northwestward-trending lineaments. He suggested further (1955, p. 62) that these centers form three subparallel northwestward-trending "porphyry lines" that reflect planes of weakness in the subcrust. These porphyry lines are (a) the Henry porphyry line connecting the Henry and Carrizo Mountains, (b) the Ute porphyry line joining the Abajo and Ute Mountains, and (c) the La Sal porphyry line joining the La Sal and La Plata Mountains. All trend about N. 45° W.

The evidence for Kelley's porphyry lines seems tenuous. The porphyry lines commonly join only two laccolithic centers (for example, Henry-Carrizo, Abajo Ute), and if different laccolithic centers are joined (for example, Abajo-La Sal, Carrizo-Ute, La Plata-Rico), lines with wholly different trends result.

The laccolithic centers, to most of us who have studied them, are clearly younger than the tectonic structural features, and do not appear to have been influenced by the tectonic features in any way. This lack of relationship has been noted for the Henry Mountains (Hunt, 1953, p. 88), the La Sal Mountains (Hunt, 1958), the Ute Mountains (E. B. Ekren and F. N. Houser, written communication, 1957), the Carrizo Mountains (J. D. Strobell, oral communication, 1957) and the Abajo Mountains.

The Abajo Mountains area, as an example, is near three major tectonic units (fig. 16): (a) the Paradox fold and fault belt to the northeast, which is marked by northwest-trending salt anticlines, faults, and folds, (b) the Blanding basin to the southeast, which is a deep structural basin whose axis is concave northeastward, and (c) the Monument upwarp to the west, which is an asymmetric anticline whose axis trends northward and can be traced for about 90 miles from Marsh Pass, Ariz., to its north terminus west of Shay Mountain. The location of the Abajo Mountains does not seem to have been determined by any of these units.

In contrast to Kelley's concept of a more or less parallel alinement of the laccolithic centers, Shoemaker (1956, p. 160) suggested that the general distribution of the laccolithic groups on the Colorado Plateau may indicate the space available for discrete "cells" of magma, each cell being related to a much broader structure in the subcrust. A serious objection to Shoemaker's concept is the uniform composition of the porphyry that makes up the laccolithic centers, for the porphyry in the Abajo Mountains is similar to that in the Henry, Carrizo, La Sal, and Ute Mountains (fig. 14). If cells of magma were in fact responsible for each laccolithic mountain, the parent rock (which presumably underwent local anatexis to form the cells) must have been of unusually uniform composition. Further, each cell must have formed at about the same time and undergone an almost identical crystallization sequence.

I suggest that each laccolithic center is the result of an apophysis of magma which extended upward from a much larger intratelluric magma chamber of uniform composition. The actual location of the laccolithic centers would be determined by zones of weakness in the subcrust, these zones having formed possibly wherever the northeastward-trending structures in the Precambrian strata were cut either by the northwestward-trending structures of the Permian and Pennsylvanian or by the northward-trending structures of Laramide age.

STRUCTURAL FEATURES UNRELATED TO INTRUSIONS

GRABENS

Two grabens cross the Abajo Mountains area (fig. 17). The Shay graben crosses the northwest flank, and the Verdure graben crosses the south flank of the mountains.

SHAY GRABEN

The Shay graben extends for about 19½ miles from its western terminus on Maverick Point in the Elk Ridge area (center sec. 14, T. 33 S., R. 20 E.) to its east end near Peters Point Ridge in Dry Valley (SW¼ sec. 4, T. 32 S., R. 23 E.). The graben trends about N. 65° E. and is about half a mile wide for most of its length. In gross aspect the graben is straight; in detail, however, it is convex to the northwest where it crosses the north flank of the mountains (fig. 17).

The faults that flank the graben converge downward at dips that range from 70° to 80°, and, as far as can be determined, the fault plane surfaces are smooth. Both of the faults are tentatively classified as dip-slip; both trend diagonally across the strike of the beds.

The North Shay fault, along the north side of the graben, is poorly exposed, and the topography commonly gives no hint of its presence. In the NE¼ sec. 21, T. 32 S., R. 22 E., the fault crops out at the head of a small gully as a brecciated zone 6 to 10 feet wide cemented by calcite and limonite. Here the fault trends about N. 73° E., dips about 78° S., and cuts the Navajo Sandstone. About half a mile to the southwest in the NW¼ of the same section, the fault is exposed along the west valley wall of Indian Creek where it offsets the Wingate Sandstone and Kayenta Formation. The fault is more or less concealed beneath dune sand and pediment deposits where it crosses the broad benches that flank the north end of Shay Mountain, but it is exposed along the valley walls of the deep canyons that separate these benches.

The North Shay fault, about 21 miles long, can be traced from the SE¼ sec. 16, T. 33 S., R. 20 E., in the Elk Ridge area to the center of sec. 4, T. 32 S., R. 23 E., in the Lisbon Valley area. The fault extends westward about 1½ miles beyond the west end of the Shay graben (Lewis and Campbell, 1964). The throw on the fault ranges from 150 to 320 feet in the Abajo Mountains area and from 0 to 100 feet in Dry Valley (G. W. Weir, oral communication, 1956.)

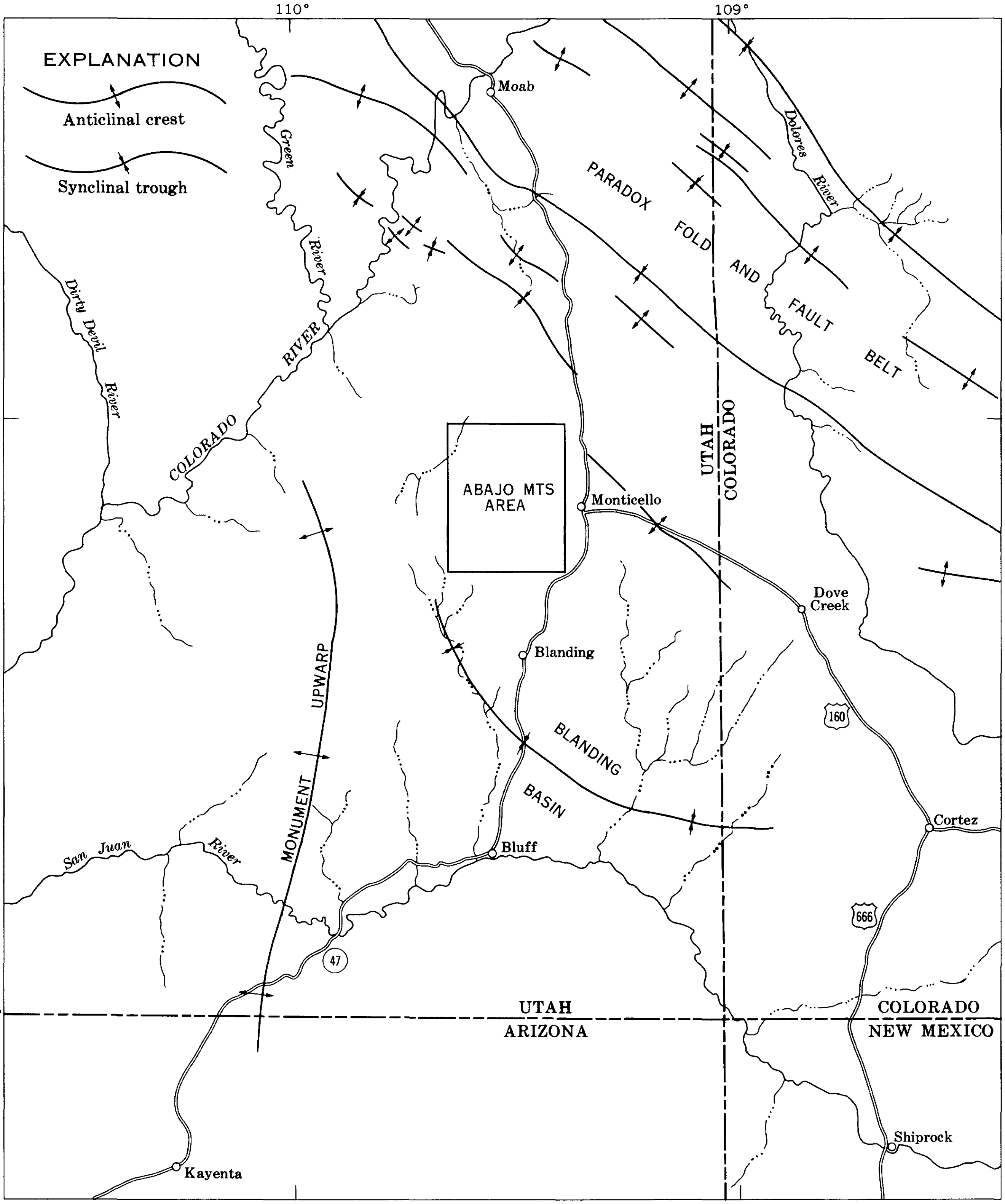


FIGURE 16.—Major tectonic units near the Abajo Mountains.

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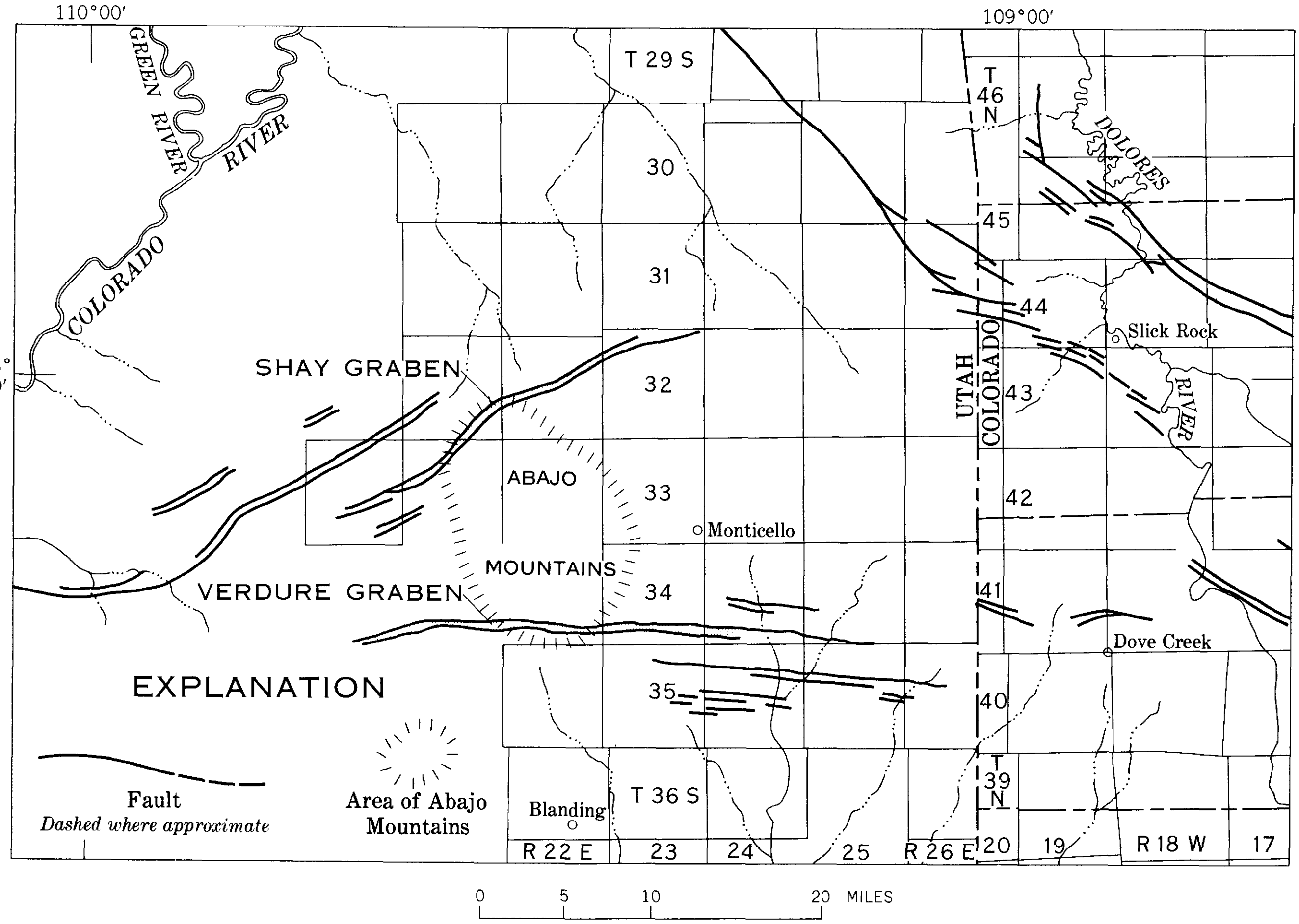


FIGURE 17.—Map showing the relations of the Abajo Mountains to the Shay and Verdure grabens. The fact that the grabens extend far beyond the mountains suggests that the grabens are unrelated to the mountains.

The South Shay fault, along the south side of the Shay graben, is well marked by triangular faceted spurs that extend across secs. 29 and 30, T. 32 S., R. 22 E., along the northeast flank of Shay Mountain. These facets, which face northwest, indicate the relative resistance to erosion of the sedimentary beds that flank the fault. South of the fault the resistant Kayenta Formation caps the upland in which the facets have been carved, whereas north of the fault the easily eroded Navajo Sandstone forms the ground surface. Farther east in sec. 21, T. 32 S., R. 22 E., where the fault cuts across Indian Creek, a distinct escarpment about 250 feet high is formed. This escarpment also results from the relation of the resistant Kayenta cap south of the fault to the easily eroded Navajo Sandstone north of the fault.

In the center of the N½ sec. 22, T. 32 S., R. 22 E., the fault trace is marked locally by a calcite- and limonite-cemented fault breccia which stands as a ridge about 10 feet above the surrounding ground. The ridge ranges in thickness from 1 to about 10 feet. All strata adjacent to the fault are severely jointed, and the joints parallel the fault trace which in this locality trends about N. 60° E. The fault dips about 76° N.

The South Shay fault, about 23 miles long, extends from the center of sec. 14, T. 33 S., R. 20 E., in the Elk Ridge area to the center of the S½ of sec. 32, T. 31 S., R. 24 E., in the Lisbon Valley area. The west edge of the South Shay fault merges with the North Shay fault, and its east edge extends about 5 miles east of the east end of the Shay graben. The throw on the South Shay fault ranges in the Elk Ridge area from 20 to 300 feet (R. Q. Lewis, Sr., oral communication, 1957), in the Abajo Mountains area from 80 to 300 feet, and eastward in Dry Valley from 0 to about 100 feet (G. W. Weir, written communication, 1956).

The age of the North and South Shay faults is unknown. Baker (1933, p. 73) has suggested that the Shay graben may have formed "* * * contemporaneous with and due to the intrusions of the laccoliths and the elevations of the mountains." The extension of the

Shay graben far beyond the Abajo Mountains and its convex bow to the northwest where it crosses the north flank of the mountains (fig. 17) suggest that the graben was established before the laccoliths were emplaced and then bowed northwestward as the mountains were elevated.

VERDURE GRABEN

The south edge of the mountains is crossed by the Verdure graben (fig. 17), which, for part of its length, appears as a broad steep-walled even-floored canyon about half a mile wide. In the Abajo Mountains area the graben extends eastward for 13¾ miles cutting across Allen Canyon, Dry Wash, Johnson Creek, and Recapture Creek. It widens and narrows erratically, and locally, near its west edge, it thins to about a tenth of a mile. The west terminus of the graben, in the NW¼ sec. 35, T. 34 S., R. 20 E. (unsurveyed), is near the north end of South Cottonwood Wash in the Elk Ridge area. From that point the graben extends eastward for about 23 miles as a huge downthrown block of sedimentary strata. Its east end is in the NE¼ sec. 32, T. 34 S., R. 24 E., along the west valley wall of Montezuma Canyon (L. C. Huff, oral communication, 1957). The Verdure graben is almost straight in the Abajo Mountains area, but in its entirety it forms a broad curve having its convex side to the north. Thus, its N. 80° E. trend through the Elk Ridge area alters imperceptibly in the Abajo Mountains and the Montezuma Canyon areas to an easterly and finally to a S. 80° E. trend (fig. 17).

Exposures along the graben flanks are poor and consequently it is not possible to determine the direction of dip of the two marginal faults. They are thought to converge downward, and to range in dip from 80° to vertical. Both are tentatively classified as dip-slip.

Of the two faults that flank the Verdure graben, the North Verdure fault is longer, has more throw, and is better exposed. It has been traced from the center of the N½ sec. 34, T. 34 S., R. 20 E., in the Elk Ridge area for about 32¼ miles to the center of the N½ sec. 1, T. 35 S., R. 25 E. It continues to the east beyond this point, but the east terminus has not been determined. The fault is much longer than the graben, for it extends about half a mile west of the west edge of the graben (R. Q. Lewis, Sr., oral communication, 1956) and at least 10 miles east of the east terminus of the graben (L. C. Huff, oral communication, 1957).

In the Abajo Mountains area the North Verdure fault is nowhere clearly exposed. It trends generally eastward and dips southward at about 80°. The throw on the fault is about 200 feet in the Elk Ridge area, about 250 feet in the Abajo Mountains area, and about 180 feet in the Great Sage Plain area.

In the southeast part of the Abajo Mountains area, the North Verdure fault is at the base of a steep-walled escarpment capped by the resistant Dakota Sandstone and Burro Canyon Formation. Where this resistant cap bas been removed, the soft beds on both sides of the fault weather alike and no escarpment is formed. Here the fault trace is difficult to follow. The main drainage courses, Recapture and Johnson Creeks, Dry Wash, and Allen Canyon, cross the fault with no apparent offset. In a few places, small streams follow the fault trace.

The South Verdure fault extends about 24 miles from its west terminus in the center of the W½ sec. 35, T. 34 S., R. 20 E. (unsurveyed) in the Elk Ridge area to its east edge in the center of the E½ sec. 32, T. 34 S., R. 24 E. in the Great Sage Plain area. For most of its extent it parallels the North Verdure fault, although locally in the southwest corner of the Abajo Mountains area it converges on that fault, and the graben is narrowed drastically (pl. 1).

The South Verdure fault is nowhere clearly exposed in the Abajo Mountains area. In general, its trace is eastward and its dip is to the north, ranging from 70° to nearly 90°. The throw on the South Verdure fault is about 80 feet in the Elk Ridge area, about 150 feet in the Abajo Mountains area, and about 180 feet in the Montezuma Canyon area.

In the southeast corner of the mapped area, the South Verdure fault appears as a steep-walled escarpment capped by the Dakota and Burro Canyon. This caprock is overlain by about 150 feet of the Mancos Shale, which in turn is overlain by about 50 feet of unconsolidated pediment deposits (fig. 18). As with the North Verdure fault, in the places where the caprock has been removed, the fault trace is difficult to detect.

The youngest formation offset by the marginal faults of the Verdure graben is the Mancos Shale of Late Cretaceous age.

Near Recapture Creek in secs. 35, 25 and 36, T. 34 S., R. 22 E. (unsurveyed), the sedimentary strata in the Verdure graben are broken by small faults which strike northward, normal to the trend of the graben. These faults probably do not cut and displace the faults that flank the graben.

Two dikes are along the South Verdure fault, and the Rocky Trail laccolith (p. 73) is within the graben (secs. 26 and 35, T. 34 S., R. 22 E., unsurveyed; pl. 1). The laccolith ends abruptly against the North and South Verdure faults. One of the dikes, in the

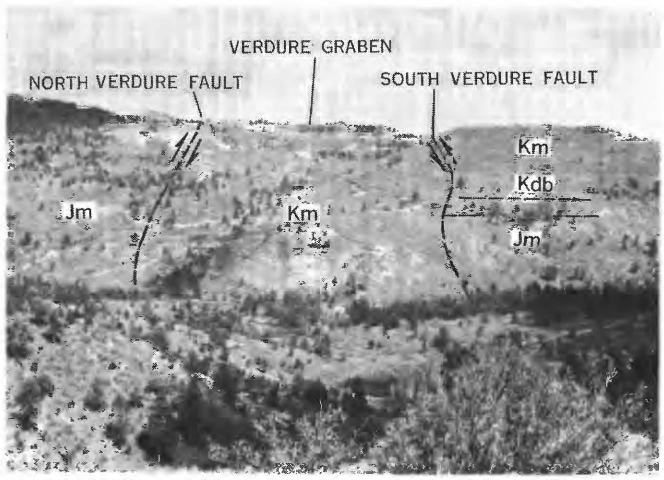


FIGURE 18.—Part of the Verdure graben exposed along the east valley wall of Johnson Creek. (Jm, Morrison Formation; Kdb, Dakota Sandstone and Burro Canyon Formation; Km, Mancos Shale).

W½ sec. 34, T. 34 S., R. 22 E. (unsurveyed), is about 50 feet wide and 600 feet long, and is along and collinear with the South Verdure fault. The other dike is an eastward extension of the southeast edge of the Rocky Trail laccolith (center sec. 35, T. 34 S., R. 22 E., unsurveyed). This dike, about 50 feet wide and 750 feet long, also is along and collinear with the South Verdure fault.

Inasmuch as neither fault breccia nor gouge is along either the laccolithic flanks or the dikes, I suggest that the faults antedate the intrusions. By implication, then, the Verdure graben was already established before intrusive masses domed the area. When the magma was intruded, the fault planes may have served as channelways to form the dikes and the laccolith. If so, the linearity of the north and south flanks of the Rocky Trail laccolith, in large measure, was controlled by the preexisting fault planes.

The Shay and Verdure grabens are very similar. The Verdure graben extends beyond the Abajo Mountains in much the same manner as does the Shay graben (fig. 17). They are of comparable length and width; the faults that bound them are high-angle faults that converge downward and have similar amounts of throw. The two grabens are part of a more extensive fracture system that extends through southeastern Utah into southwestern Colorado (fig. 17). These similarities suggest that the two grabens were formed synchronously and by the same stresses. The dikes and laccolith in the Verdure graben and the northwesterly bowing of the Shay graben imply that the two grabens were in existence before the emplacement of the intrusions. The grabens are neither concentric with nor radial to the dome formed by the Abajo Mountains, and this lack of pattern strengthens the suggestion that they were not formed by the elevation of the mountains. The absolute age of the grabens is unknown. The relative age, however, is suggested by the fact that the faults which bound the Verdure graben cut and offset the Mancos Shale of Late Cretaceous age (p. 45). The age of the grabens, therefore, must be Late or post-Cretaceous, but earlier than the elevation of the mountains.

IGNEOUS INTRUSIONS AND RELATED STRUCTURAL FEATURES

The strata exposed in the mountains, deformed by the intrusions, reflect the shape of the intrusive body that underlies them. Folds of two sizes have been formed. First are those few huge folds best described as domes which are probably related to the injection of a major igneous body, here tentatively classified as a stock. These domes are measured in miles. The strata that form their flanks dip radially away from the crest for considerable distances. Examples of these folds are Shay Mountain (a dome) and the Johnson Creek dome (pl. 1.). Second are the many minor folds, chiefly anticlines, formed by the satellite intrusions emanating from the stocks. Included in this category are the folds formed by laccoliths, sills, or bosses of igneous rock. Strata that were folded as a result of a laccolithic intrusion dip steeply, especially along the flanks and distal end of the laccolith. These dips are of local extent and flatten rapidly.

THE INTRUSIONS

The Abajo Mountains are very similar in structure to the Henry Mountains in that each mountain group consists of a central parent stock surrounded by satellite laccoliths. Each stock is encircled by a zone of shattered sedimentary rocks which have been intruded by igneous dikes, sills, and bosses (Hunt, 1953, p. 90).

The mountain groups in the Henry Mountains form relatively distinct topographic entities; in contrast, the topographic entities in the Abajo Mountains are not as clear (pl. 2). However, once the stocks in the Abajo Mountains are located, their related laccoliths may be postulated from the basic plan of a stock encircled by laccoliths, and then the fundamental pattern of the whole range may be determined (fig. 19).

The Abajo Mountains consist of two known stocks together with their related laccoliths and two inferred stocks whose general position is shown by domed sedimentary rocks and whose composition is suggested by subsidiary intrusions (pl. 4; table 4).

The distribution of the stocks is indicated by the topography. In general, the Abajo Mountains can be divided into two unequal parts: the main mass of the mountains which occupies about four-fifths of the high country, and the huge dome known as Shay Mountain which occupies about one-fifth. The main mass of the mountains can be further subdivided into two parts, West Mountain and East Mountain (pl. 2), each of which is formed by a stock and its associated laccoliths. Shay Mountain, connected by a low ridge to the north end of the main mass of the mountains, is probably underlain by a third stock whose composition and texture are suggested by the many minor dikes, sills, and laccoliths exposed on the flanks of the dome.

A fourth stock may underlie the Johnson Creek dome at the south flank of the mountains. This stock(?) has not influenced the topography as much as the other stocks.

The pattern of the mountains, therefore, appears to be the result of the spacing of the stocks and their attendant laccoliths. In detail, many of the large laccoliths have at their distal ends smaller laccoliths that form a lobate fringe around them. These smaller bodies are here called fringe laccoliths.

In all, 31 laccoliths have been recognized; they can be divided into three categories: (a) contiguous laccoliths—individual distinct laccoliths attached at their proximal end to a parent stock; (b) fringe laccoliths—laccoliths formed around the flanks and distal end of a contiguous laccolith; and (c) discrete laccoliths—laccoliths which cannot be clearly related either to a stock or to a contiguous laccolith (fig. 20).

The laccoliths are chiefly in four sedimentary units, the Cutler, the Chinle, the Morrison, and the Mancos (table 4), and it is these strata that have been deformed the most.

By the above classification, the East Mountain stock is encircled by six contiguous laccoliths and nine fringe laccoliths (p. 47–62; table 4). Of these 15 laccoliths, nine are in the Mancos Shale, and six are in the Morrison Formation. The West Mountain stock is encircled by five contiguous laccoliths (p. 62–66), four of which are in the Morrison Formation, and one is emplaced chiefly in the Mancos Shale. Five contiguous laccoliths are provisionally attributed to the buried Johnson Creek stock (?) (p. 66–71). Of these, one is in the Cutler Formation, one is in the Chinle Formation, and three are in the Morrison Formation. Two contiguous laccoliths are related to the Shay Mountain stock(?) (p. 71–73); both are chiefly in the Morrison Formation. Four laccoliths cannot be clearly related either to a stock or a contiguous laccolith, and are classed as discrete laccoliths. Of these, one is in the Mancos, and the other three are in the Morrison Formation (table 4).

The laccoliths commonly appear in one of four ways and reflect the stage of erosion (fig. 21):

1. As anticlines in which igneous rock is not exposed and where an igneous core must be inferred (examples: the Spring and Corral anticlines; see fig. 21*A*; p. 58–59).
2. As partly denuded laccoliths, where some of the sedimentary cover has been removed and part of the laccolith is exposed (fig. 21*B*; p. 56, 59). In these, the flanks and distal end of the laccolith are rimmed by steeply dipping hogbacks of sedimentary rocks. In places the laccolith is overlain by remnants of the once continuous sedimentary cover (examples: Gold Queen and North Robertson Pasture laccoliths).
3. As completely denuded laccoliths exposed as porphyry masses (fig. 21*C*; p. 60, 65). In this stage, the sedimentary cover has been almost completely removed, the laccolith is exposed in its entirety, and only small remnants of the former sedimentary cover are still preserved on its flanks (examples: the South Peak and Mount Linnaeus laccoliths). The attitudes of these remnants reflect the former structure.
4. As dissected laccoliths where erosion has reduced the laccolith to a few igneous knobs (example: the Abajo Peak laccolith (fig. 21*D*; p. 54).

EAST MOUNTAIN STOCK AND RELATED LACCOLITHS

The East Mountain stock, exposed along the section line between secs. 12 and 13, T. 34 S., R. 22 E. (unsurveyed), appears as an oval mass whose long axis trends about N. 40° W. The stock is about ½ mile long and about ¼ mile wide at its widest part. Topographically it forms a low hill between the higher masses of the Abajo Peak laccolith to the north and the South Peak laccolith to the south. The margins of the stock are not clearly recognizable in many places, chiefly because the stock is encircled by a zone of shattered sedimentary rocks that have been intruded by igneous dikes and sills—the entire mass having been so disturbed that detailed mapping of the units is almost impossible. This shatter zone is ill-defined, and its margins are arbitrary.

The East Mountain stock consists chiefly of quartz diorite porphyry and quartz diorite porphyry breccia, each rock type grading into the other.

Much of the stock is cut by closely spaced fractures that trend either about N. 68° W., or about N. 60° E. Most of the fractures are vertical or nearly so, although some that trend northwestward dip northeastward. Some of these are about 1 inch apart, but in places they are no more than one-eighth inch apart and mask the original nature of the rock.

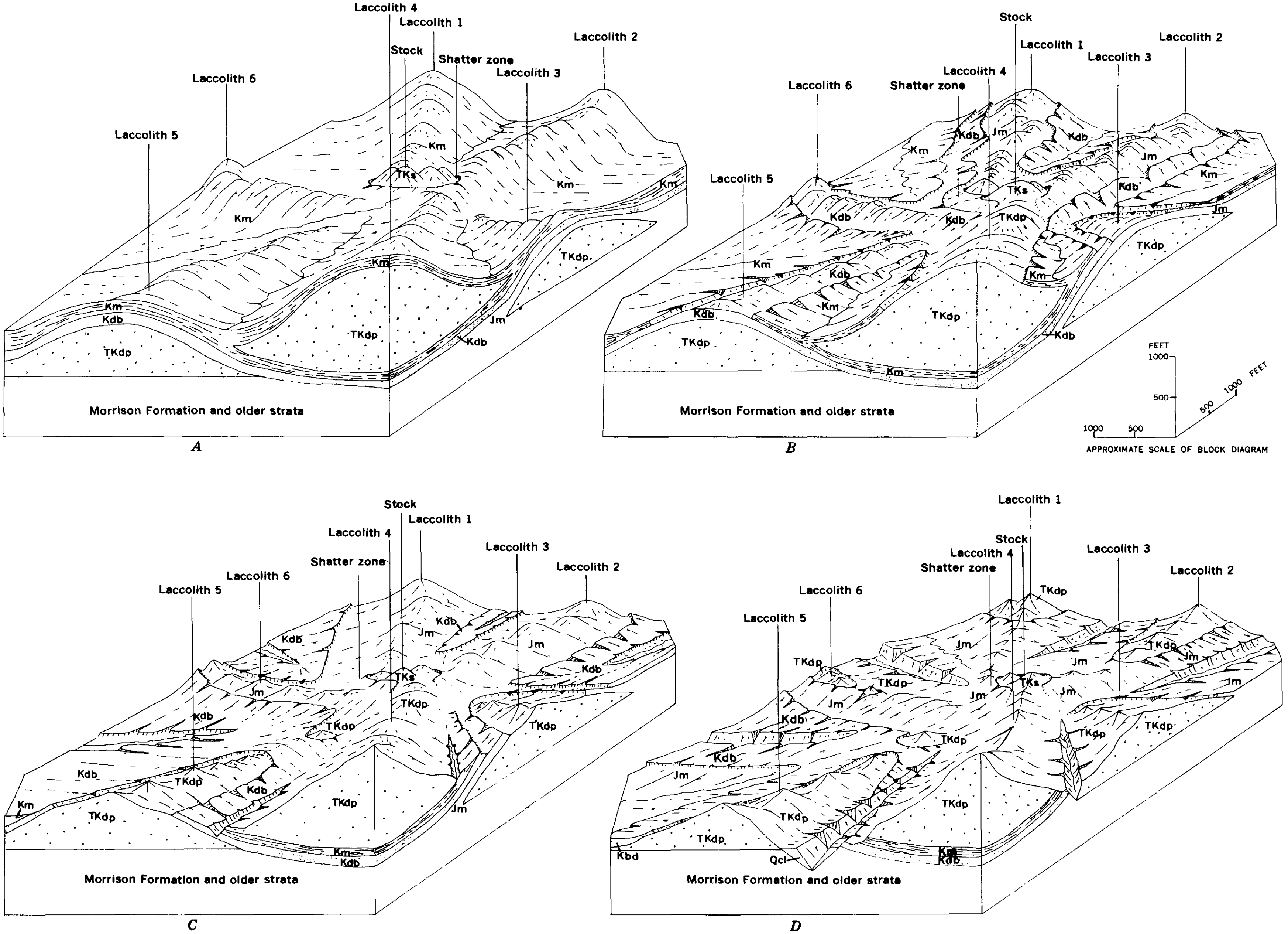


FIGURE 19.—Block diagrams showing the radial arrangement of laccoliths about a parent stock and the progressive denudation of the intrusive complex. (Km, Mancos Shale; Kdb, Dakota and Burro Canyon; Jm, Morrison Formation; T Kdp, quartz diorite porphyry; T Ks, stock, quartz diorite porphyry and quartz diorite porphyry breccia; Qcl, colluvium.)

A, Laccoliths have been emplaced and the area has been partly eroded. All but one of the laccoliths are below the Dakota and Burro Canyon and arch that unit; laccolith 4 is in the Mancos Shale. All the laccoliths are expressed as anticlines and the only igneous mass exposed is the stock. *B*, Continued dissection results in the gradual stripping of the sedimentary cover. Different sedimentary units are exposed above the various laccoliths. The Mancos Shale has been removed from the roof and flanks of laccolith 4, which now appears as a partly exhumed porphyry cap that extends unbroken through a shatter zone. *C*, As erosion continues, more laccoliths are exposed (3, 4, and 5). The remaining loccoliths are still concealed and appear as partly dissected anticlines. *D*, All the laccoliths are exposed in part or in whole. Dissection has now advanced far enough to leave the floors of some laccoliths perched above the stream floors (laccoliths 4 and 5). A situation comparable to this exists in the Abajo Mountains. The laccoliths emplaced in the Mancos Shale have had their sedimentary cover removed, whereas those in the Morrison Formation are either partly exhumed or still underlie anticlines.

The fractures are remarkably straight; where closely spaced, they appear as a braided network that can be traced for 15 to 20 feet before it is concealed by detritus. The fractures form a crude zone that trends about N. 80° E., is about 2,000 feet wide, and extends from one side of the stock to the other.

Many of the fractures are filled with silica, and, in a few, bipyramidal grains of quartz have formed that are as much as one-fourth inch in diameter. In places the fractures are filled by a well-knit mesh of euhedral quartz crystals.

The fractured rocks have been intensely altered and now appear as dark yellowish-orange (10*YR* 6/6) areas that contrast with the light gray of adjacent moderately fractured and altered porphyry. Pyrite cubes, widespread in the partly altered rocks, are scarce or nonexistent in the quartz veinlets that fill the fractures.

Most of the active mining and prospecting in the Abajo Mountains area was carried on in the intensely altered areas. The mines seem to have been restricted either to the rocks that form the stock or to the shatter zone. Many of the mines and prospect pits were dug along fracture zones, and it seems likely that the drifts of these mines (whose portals are now closed as a result of caving) followed these zones.

Topographically the shatter zone appears either as steep slopes along the flanks of the stock or as low divides that separate the stock from its associated laccoliths. The zone ranges in width from about 200 to 3,000 feet, being widest near the southwest edge of the stock.

Sedimentary strata that can be recognized in the shatter zone include the Morrison Formation, the Dakota and Burro Canyon, and the Mancos Shale. Irregular blocks of these units are tilted and tipped into all conceivable attitudes. Despite their proximity to the stock, the rocks have been only slightly baked and metamorphosed. They have, however, been severely fissured, and commonly they break into small angular fragments that form a thick cover which more or less completely conceals the underlying units. Because of this float, it is not everywhere possible to determine where the shatter zone ends and the relatively undeformed sedimentary units begin.

The igneous bodies in the shatter zone are composed of quartz diorite porphyry that is identical to the porphyry in the stocks and laccoliths. Most of the intrusions in the shatter zone appear as small dikes of uneven width, as sills, or as small bosses of igneous rock. Commonly these intrusions are more resistant than the adjacent fractured sedimentary strata, and they form irregularly shaped knobs that stand topographically above the surrounding area.

Fifteen laccoliths of different sizes and shapes can be related to the East Mountain stock (fig. 20). In addition, three of the four laccoliths classified as discrete (table 4) may be related to the East Mountain stock. These are the Pole Creek and the laccoliths(?) that underlie the Corral (p. 58) and the Spring Creek anticlines (p. 59).

The laccoliths are tonguelike in outline; their proximal ends are attached either to the stock or to another laccolith. Their distal ends tend to be blunt, and sedimentary strata wrapped over these ends locally dip as much as 50° outward. Both laccolithic crests and flanks show minor irregularities which are reflected in the sedimentary cover as small folds that influence present-day drainage. Where exposed, the laccolithic floors are undulatory, crosscutting the sedimentary strata. Generally the distal ends of the laccoliths have arched the overlying strata, which now appear either as an unbroken sedimentary cover or as remnants on the laccolithic flanks (fig. 21).

All the laccoliths are composed of the same type of porphyry, and textural differences (if any) between laccoliths commonly are slight.

Although the laccoliths are similar in structure and in gross composition, their shapes vary widely. Some are symmetrical, others asymmetrical, and no direct relation can be seen between one type and the other. Some are elongate and narrow, and appear as thin fingers radiating from a common center; others are broad and semicircular in plan view. They range in size from 1/4 mile wide to about 2 miles long and 2 miles wide. Most are about 1 1/2 miles long by about 1 mile wide (table 4). The thicknesses of the laccoliths also vary widely. Some of the smaller ones are about 600 feet thick at their thickest part (not necessarily the proximal end), whereas some of the larger laccoliths are estimated to have been as much as 2,600 feet thick when originally emplaced (pl. 4; table 4). The

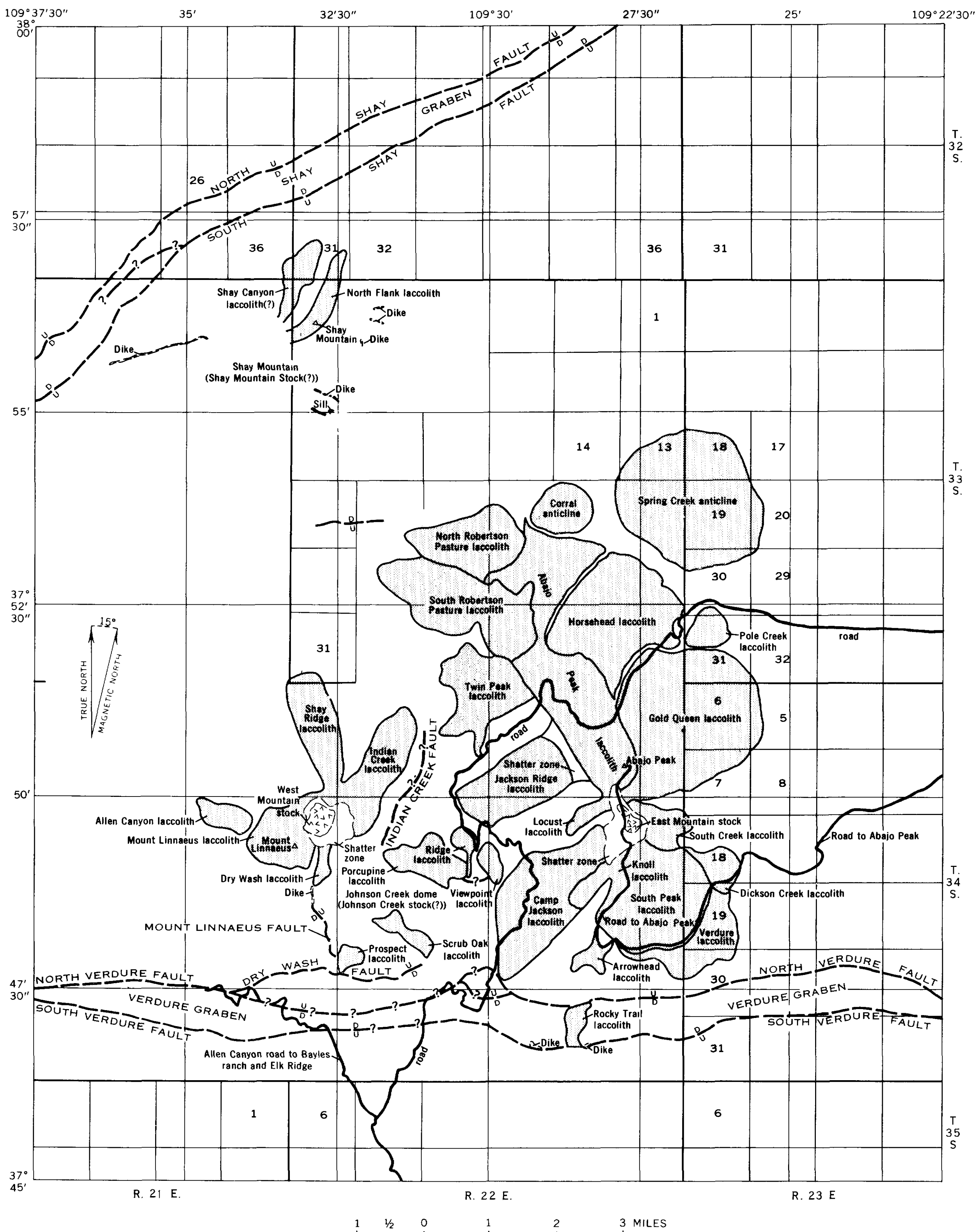


Figure 20.—The Abajo Mountains area showing the general distribution of the laccoliths about their parent stocks. The two known stocks (the East Mountain and the West Mountain stocks) are shown by checks. The patterned areas represent the laccoliths and indicate their probable extent shortly after emplacement.

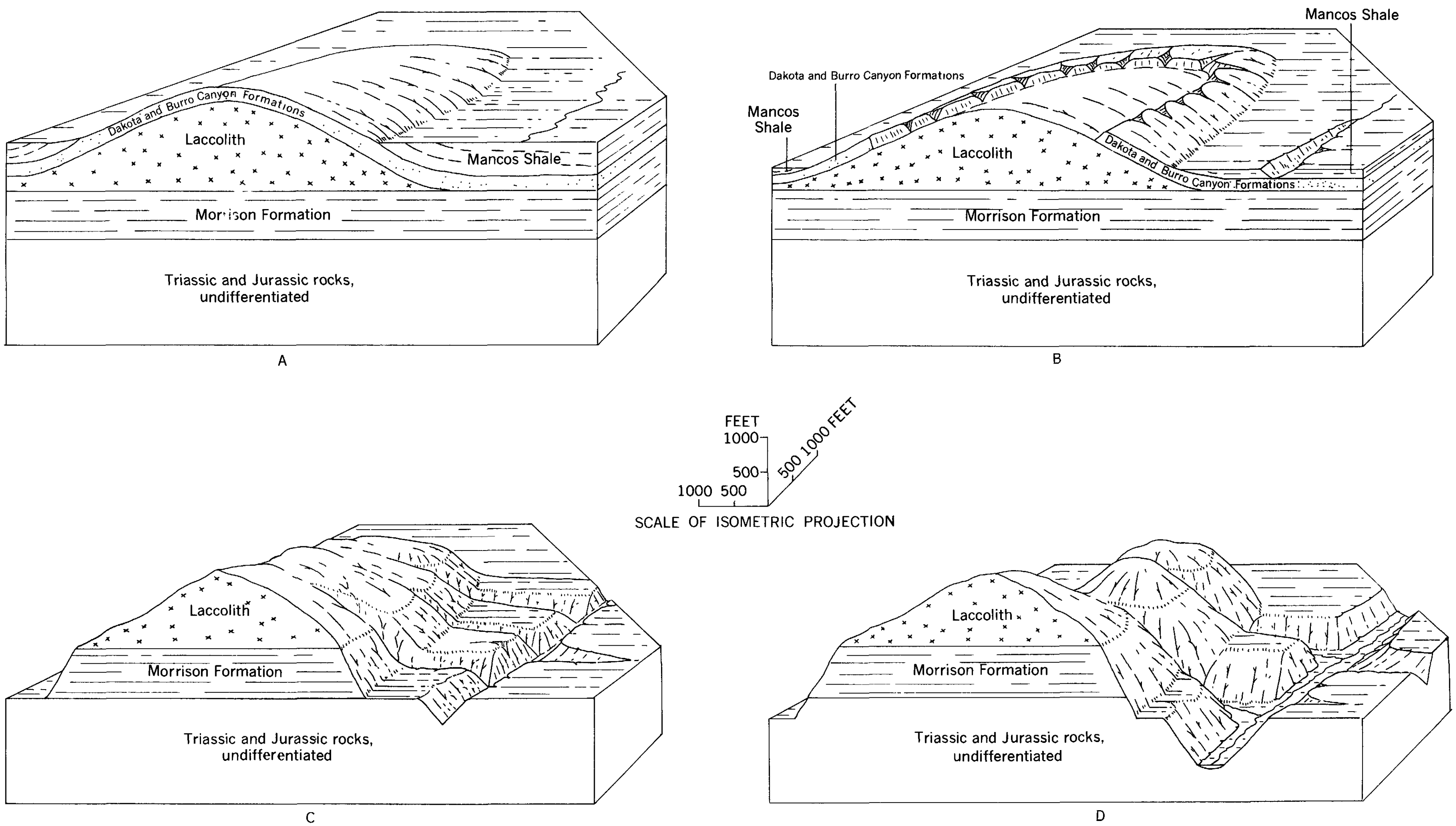


FIGURE 21.—Block diagrams illustrating the progressive denudation of a concealed laccolith. *A*, Laccolith completely concealed beneath sedimentary strata that appear as an anticline. *B*, Laccolith partly exposed as a result of erosion of the sedimentary cover, which now remains as hogbacks. *C*, Laccolith completely denuded, and perched high above the stream floors as a result of continued differential erosion. *D*, Denuded laccolith eroded and partly separated into distinct remnants; general laccolithic configuration almost destroyed. Height above stream floors increased.

TABLE 4.—*Data about laccoliths in the Abajo Mountains area*

Laccolith			Sedimentary rocks directly underlying laccolith	Sedimentary rocks directly overlying laccolith	Approximate location (Section(s), township, range)	Approximate trend (from parent stock to feeder laccolith)	Estimated dimensions				
Contiguous	Fringe	Discrete					Length (miles)	Width (miles)	Thickness when emplaced (miles)	Area exposed (square miles)	Volume when emplaced (cubic miles)
KNOWN STOCKS											
East Mountain stock											
Abajo Peak			Mancos Shale	Mancos Shale	2, 3, 11, 12, T. 34 S., R. 22 E.*	N. 16° W	4.0	1.0	0.08–0.53	1.70	0.65
	Locust		Dakota Sandstone and Burro Canyon Formation.	do	11, 14, T. 34 S., R. 22 E.*	S. 45° W	.6	.2	.11	.08	.01
	Jackson Ridge		Mancos Shale	do	9, 10, T. 34 S., R. 22 E.*	S. 65° W	1.6	.6	.27	1.34	.12
	Twin Peak		do	do	4, T. 34 S., R. 22 E.;* 33, T. 33 S., R. 22 E.*	S. 77° W	1.3	1.1	.27	.94	.17
	South Robertson Pasture.		do	do	28, 29, and 32, T. 33 S., R. 22 E.*	N. 82° W	1.4	1.0	.27	1.65	.14
	North Robertson Pasture.		Morrison Formation	Dakota and Burro Canyon.	21 and 22, T. 33 S., R. 22 E	N. 40° W	1.4	1.3	.34	.95	.22
	Horsehead		Dakota and Burro Canyon.	Mancos Shale	25, 26, 35, and 36, T. 33 S., R. 22 E.*	N. 35° E	1.7	1.3	.49	2.27	.53
		Pole Creek	do	do	31, T. 33 S., R. 23 E	N. 63° E	1.0	.6	.18	.34	.06
		Laccolith under Corral anticline.	Morrison Formation(?)	Dakota and Burro Canyon.	22, 23, T. 33 S., R. 22 E.*	N. 20° E. (?)	.6	.8	.16		.08
		Laccolith under Spring Creek anticline.	do	Morrison Formation	13 and 24, T. 33 S., R. 22 E.; 18, 19, T. 33 S., R. 23 E.	N. 45° E. (?)	1.8	1.4	.12		.35
Gold Queen			Morrison Formation	do	1, T. 34 S., R. 22 E.;* 6, T. 34 S., R. 23 E.	N. 72° E	1.9	2.0	.28	.96	.92
South Creek			Mancos Shale	Mancos Shale	13, T. 34 S., R. 22 E.*	S. 85° E	.8	.6	.15	.40	.04
South Peak			Morrison Formation	do	13 and 24, T. 34 S., R. 22 E.*	S. 12° E	1.4	1.3	.30	2.22	.23
	Dickson Creek		Dakota and Burro Canyon.	do	18, T. 34 S., R. 23 E	N. 88° E	.6	.6	.08	.32	.01
	Verdure		do	do	19 and 30, T. 34 S., R. 23 E	S. 62° E	.6	1.3	.11	.76	.05
	Arrowhead		Morrison Formation	Morrison Formation	23 and 26, T. 34 S., R. 22 E.*	S. 37° W	1.0	.9	.19	.15	.05
Knoll			do	do	14 and 23, T. 34 S., R. 22 E.*	S. 55° W	.5	.3	.06	.11	.01±
Camp Jackson			do	do	14, 15, 22, 23, 26, 27, T. 34 S., R. 22 E.*	S. 30° W. (?)	2.0	1.2	.15–.30	.16	.33
West Mountain stock											
Shay Ridge			Morrison Formation	Morrison Formation	6 and 7, T. 34 S., R. 22 E.*	N. 2° E	2.2	0.9	0.34	0.11	0.27
Indian Creek			do	do	5 and 8, T. 34 S., R. 22 E.*	N. 42° E	1.4	.9	.38	.65	.24
Dry Wash			do	do	18, T. 34 S., R. 22 E.*	S. 18° E	.5	.5	.11	.24	.01
Mount Linnaeus			Mancos Shale	Mancos Shale	13, T. 34 S., R. 21 E.;* 18, T. 34 S., R. 22 E.*	S. 35° W	.8	.9	.23	.75	.08
Allen Canyon			Morrison Formation	Morrison Formation	11, 12, 13, 14, T. 34 S., R. 21 E.*	N. 84° W	1.6	.5	.11	.29	.03

INFERRED STOCKS

Johnson Creek stock(?)

Prospect			Cutler Formation	Cutler Formation	19, 20, 29, 30, T. 34 S., R. 22 E.*	S. 50° W	0.7	1.3	0.27	0.09	0.06
Scrub Oak			Chinle Formation	Chinle Formation	20, T. 34 S., R. 22 E.*	S. 50° W	.5	.8	.11	.25	.01
Porcupine			Morrison Formation	Entrada Sandstone	16 and 17, T. 34 S., R. 22 E.*	N. 80° W.(?)	1.3	.7	.49	.54	.15
Ridge			do	Morrison Formation	16, T. 34 S., R. 22 E.*	N. 30° W	.4	.4	.15	.10	.01
Viewpoint			do	do	15, 16, T. 34 S., R. 22 E.*	N. 80° E	.2	.1	.08	.20	.01

Shay Mountain stock(?)

Shay Mountain(?)			Morrison Formation	Morrison Formation	Ts. 32 and 33 S., Rs. 21 and 22 E. (intersection)	N. 15° E	0.9	0.5	0.08	0.25	0.01
North Flank(?)			do	do	31, T. 32 S., R. 22 E	N. 70° E N. 20° E.	.7	.2	.11	.07	.01

LACCOLITH UNRELATED TO STOCK

		Rocky Trail	Morrison Formation(?)	Dakota and Burro Canyon.	26 and 35, T. 34 S., R. 22 E.*	?	0.5	0.3	0.11	0.14	0.01

Volume of laccoliths	4.8
Volume of stocks	.4
Total volume	5.2

*Unsurveyed.

discrete laccoliths(?) (Spring Creek, Corral, and Pole Creek) near the outer limits of the mountains are circular to oval. They may be independent intrusions unrelated to the East Mountain stock and its contiguous laccoliths, or laccolithic intrusions formed by concealed feeders of the East Mountain stock in older buried sedimentary rocks.

The competent sandstones, chiefly the Dakota and Burro Canyon, and the sandstone beds in the Salt Wash Member of the Morrison Formation, seem to have localized the laccolithic intrusions. These sandstones have served either as floors or as roofs for the magma. Thus, many of the laccoliths in the Morrison are localized in the Salt Wash Member and have as their floors, or roofs, one or another of the lenticular sandstone beds. Similarly, many of the laccoliths in the Mancos have their proximal ends resting on the Dakota and Burro Canyon, although their distal ends may be in the Mancos Shale, and in places as much as 100 feet above the Dakota and Burro Canyon. Some of the laccoliths have been intruded into the uppermost claystone beds of the Brushy Basin Member of the Morrison Formation, just below the Dakota and Burro Canyon, and have arched that sandstone into huge anticlines.

ABAJO PEAK LACCOLITH

The Abajo Peak laccolith is a feeder laccolith, and around its flanks and distal end are at least six smaller laccoliths (fig. 20; table 4). Dissection of the Abajo Peak laccolith has been so severe that only several hummocky knolls composed of porphyry remain. Its margins have long since been destroyed and one can only guess at its former size. The approximate trend and general configuration of the Abajo Peak laccolith is suggested by the spacing of its subsidiary laccoliths. At one time it probably occupied most of secs. 2, 3, 11, and 12, T. 34 S., R. 22 E (unsurveyed); (pl. 1). Its proximal end is connected to the north edge of the East Mountain stock, and from that point the laccolith extends about N. 16° W. It is estimated to have been about 4 miles long, 1 mile wide, and about 2,000 feet thick (pl. 4; table 4). Despite the severe dissection of the laccolith, small remnants of the former sedimentary cover of Mancos Shale are preserved along the laccolithic flanks and in one locality along the crest. Dips of the Mancos remnants on the west flank average 20° to the west; those on the crest are more variable and range from 10° to 30° to the south.

The laccolithic floor is exposed near the head of Indian Creek along and near the Blue Mountain-North Creek road (pl. 2). These exposures, though poor, suggest that floor is undulatory and irregular. In places the porphyry rests on the Dakota and Burro Canyon, but for most of its extent the laccolith rests on the Mancos Shale. Apparently the magma that formed the Abajo Peak laccolith was first intruded along the top of the Dakota and Burro Canyon and then cut upward into younger strata in the Mancos. In the few places where the floor is exposed, the underlying Mancos has been folded, faulted, and crumpled but only slightly metamorphosed. The zone of metamorphism does not extend more than 3 to 6 feet below the laccolith. In sharp contrast, those few remnants of the Mancos Shale that are preserved along the crest of the laccolith have been baked, indurated, and metamorphosed almost to a hornfels. The normally dark gray shale appears, where baked, as a light-gray (*N* 7), very hard, thin-bedded, intensely fractured unit. It breaks into small angular slabby fragments 1 to 2 inches on a side that form a thick scree on the mountain flanks.

The Abajo Peak laccolith was emplaced chiefly in the basal part of the Mancos Shale, and all its fringe laccoliths probably were localized in the same unit. Patches of Mancos Shale are preserved on the flanks and roofs of the denuded fringe laccoliths. These patches suggest that the present laccolithic shapes do not differ markedly from their original shapes.

The porphyry that forms these laccoliths seems to be identical in texture and composition to that in similar intrusions exposed elsewhere.

Since the emplacement of the Abajo Peak laccolith and its fringe laccoliths, the streams have cut so deeply that all the laccoliths are now perched high above the present stream bottoms and appear as porphyry caps on sedimentary strata (fig. 21*D*).

The fringe laccoliths clustered around the Abajo Peak laccolith will be described individually, beginning with the westernmost and continuing in a clockwise direction.

LOCUST LACCOLITH

The Locust laccolith along the section line between secs. 11 and 14, T. 34 S., R. 22 E. (unsurveyed; fig. 20), trends about S. 45° W. from a junction point near the proximal end of the Abajo Peak laccolith. The Locust laccolith is about six-tenths mile long, about two-tenths mile wide, and is estimated to have been about 600 feet thick when emplaced (pl. 4; table 4).

Small in contrast to many of the adjacent laccoliths, the Locust laccolith appears as a porphyry cap on a narrow linear ridge. The crest of the laccolith is sharp, undulatory, and faintly sinuous. Its flanks are steep and are covered with loose detritus. The distal end of the laccolith is marked by a gentle slope. The floor of the laccolith is nowhere clearly exposed, but on the basis of poor exposures, it is thought to be relatively smooth.

In a few places, mainly along the crest, isolated individual blocks of Mancos Shale overlie the porphyry. These blocks are interpreted as remnants of a former Mancos Shale cover that once blanketed the entire laccolith.

Because so much of the sedimentary cover has been removed, the original shape of the laccolith is in doubt, but I believe that the porphyry ridge closely coincides with the original shape. The Mancos remnants, which are still preserved on the crest and flanks of the laccolith, support this view.

The proximal end of the Locust laccolith rests on the Mancos Shale and its distal end on the Dakota and Burro Canyon. The laccolith, therefore, must have moved into older strata, away from its point of origin.

JACKSON RIDGE LACCOLITH

North of the Locust laccolith, and separated from it by the deep valley of Johnson Creek, is the Jackson Ridge laccolith that appears as a porphyry ridge covered by huge rock slides. The laccolith occupies most of secs. 9 and 10, T. 34 S., R. 22 E. (unsurveyed) and was probably injected about S. 65° W. from the Abajo Peak laccolith (fig. 20). The Jackson Ridge laccolith is about 1½ miles long and 6/10 mile wide, and is estimated to have been about 1,400 feet thick when emplaced (pl. 4; table 4). In gross aspect the laccolith appears as a huge prism having a broad base, a narrow hummocky sinuous crest, and steep, moderately dissected flanks.

Most of the strata covering the laccolith have been removed, and about four-fifths of its total length is now exposed. Near the laccolith's proximal end, a thin cover of the Mancos Shale extends across the flanks and crest. This cover is broken here and there by small igneous bosses around which the beds of the Mancos dip radially. The general attitude of the sedimentary strata on the laccolithic flanks cannot be determined, chiefly because of rock slides and the thick cover of Mancos fragments shed by topographically higher Mancos outcrops. Probably the attitudes of the beds in the Mancos which conceal the laccolithic flanks conform closely to underlying steep slopes. The beds of the Mancos on the roof of the laccolith are marked by erratic attitudes presumably reflecting the uneven hummocky top of the intrusion.

As far as can be determined from the poor exposures, the proximal end of the laccolith rests on the Dakota and Burro Canyon. The distal end of the laccolith is well exposed at Jackson Pass, and here the laccolith rests on about 100 feet of Mancos Shale. The slightly undulatory floor of the laccolith can be traced around the south flank of Jackson Ridge and, wherever exposed, the laccolith overlies 100 to 150 feet of the basal part of the Mancos Shale.

The strata that underlie the laccolith have been deformed into an elongate narrow syncline whose axis coincides closely with that of the laccolith. Whether these strata were deformed as a result of the weight of the laccolith or were deformed before the emplacement is not known. I think they were deformed before the laccolith was emplaced. In the La Sal Mountains the folding antedated the emplacement of the intrusions (Hunt, 1958, p. 314), and this sequence was probably the same in the Abajo Mountains area.

TWIN PEAKS LACCOLITH

North of the Jackson Ridge laccolith, and separated from it by Indian Creek, is the Twin Peaks laccolith, so named because of two almost identical peaks along its crest (pl. 2). In plan view the Twin Peaks laccolith is a huge irregular-shaped mass of porphyry which caps a well-dissected ridge (fig. 20).

The Twin Peaks laccolith occupies most of sec. 4, T. 34 S., R. 22 E. (unsurveyed) and of sec. 33, T. 33 S., R. 22 E. (unsurveyed). It is about 1⅓ miles long and about 1 mile wide, and is estimated to have had a maximum thickness of about 1,400 feet when emplaced (pl 4; table 4). It was probably injected S. 77° W. from the distal end of the Abajo Peak laccolith, the junction point possibly being in the SW¼ sec. 34, T. 33 S., R. 22 E. (unsurveyed), near the head of Indian Creek.

The floor of the laccolith is now about 900 feet above Indian Creek. Streams have cut deep valleys on three sides of the laccolith, and tributaries are slowly dissecting the underlying strata (chiefly Mancos Shale).

Some uncertainty exists as to whether the Twin Peaks laccolith is, in fact, an offshoot of the Abajo Peak laccolith, for no igneous connection is exposed. Moreover, an extensive boulder field in the SE¼ sec. 4, T. 34 S., R. 22 E. (unsurveyed), at the south end of the Twin Peaks laccolith, is a possible remnant of what may have been a vertical feeder for the Twin Peaks laccolith (pl. 1). The distal end of this boulder field ends at a small igneous exposure which could be a part of the unmodified feeder.

Although it is impossible to demonstrate conclusively that the Twin Peaks laccolith is related to the Abajo Peak laccolith, it is my opinion that they are related and have been separated by erosion. The general trend and configuration of the Twin Peaks laccolith (a broad distal end along the east valley wall of Indian Creek and a narrow proximal end to the east near Cooley Pass), suggest that it stems from the

Abajo Peak laccolith (pl. 2). The boulder field interpreted as an alternate feeder, may, in fact, be a true boulder field that has moved downslope gradually and finally come to rest on a knob of igneous rock—the whole simulating a vertical laccolithic feeder.

The Mancos Shale underlies the laccolith and at one time covered its flanks and roof, although dissection has long since removed most of this cover. A few remnants are still preserved, chiefly along the north flank of the laccolith.

The laccolithic floor is well exposed along the east valley wall of Indian Creek near the center of the north edge of sec. 4, T. 34 S., R. 22 E. (unsurveyed). At this locality, what may be the distal end of the laccolith forms a steep cliff at the head of one of the tributaries of Indian Creek. The contact between the porphyry floor and the underlying Mancos Shale strikes about N. 25° E., and dips about 45° SE. The attitude of the beds directly below the contact diverges slightly for they strike about N. 75° E., and dip about 20° SE. The base of the laccolith here, therefore, exhibits good crosscutting relations.

Large blocks of the Mancos Shale, intensely deformed, are enclosed in the porphyry but have been only moderately metamorphosed. This lack of intense metamorphism is also characteristic of the Mancos Shale below the porphyry. The Mancos still retains its typical features, and the only change apparent is a slight induration of the shale in a 3- to 6-inch zone along the contact. The porphyry directly above the contact has a faint chilled zone 2 to 6 feet thick in which the phenocrysts are not as large and the groundmass is finer grained. In other locations where the Mancos Shale underlies a laccolith, the shale has been folded, faulted, and crumpled. In sharp contrast, the beds of the Mancos here are undisturbed and do not seem to have undergone any severe deformation. This lack of deformation suggests that this exposure is at, or very near, the distal edge of the laccolith.

SOUTH ROBERTSON PASTURE LACCOLITH

The South Robertson Pasture laccolith occupies the major part of secs. 28, 29, and 32 of T. 33 S., R. 22 E. (unsurveyed), and forms a broad lobate mass of porphyry marked at its proximal end by a high narrow-crested sinuous ridge, and at its distal end by a low broad hummocky surface (fig. 20).

The laccolith is about 1½ miles long and about 1 mile wide, and is estimated to have been about 1,400 feet thick when emplaced (pl. 4; table 4). It was probably injected about N. 82° W. from the distal end of the Abajo Peak feeder laccolith into the basal part of the Mancos Shale.

Most of the former sedimentary cover of Mancos Shale has been removed, and the few remnants preserved on the flanks are so fragmented that it is not possible to determine the former attitude of the beds.

The floor of the laccolith is widely but poorly exposed around the rim of the broad bench that forms the south margin of Robertson Pasture, and along part of the laccolith's north margin north of North Peak (pl. 1). Along the south edge of Robertson Pasture the laccolith rests on the Mancos Shale. Northward the floor cuts downward to older beds, and near its distal edge the laccolith rests on a narrow ledge formed by the Dakota and Burro Canyon. The north margin of the laccolith is defined by a deep narrow valley that separates it from the North Robertson Pasture laccolith (pl. 2). In some places the two laccoliths are in igneous contact. Eastward, however, the Dakota and Burro Canyon and the Mancos Shale separate the two laccoliths (pl. 1). Along the north edge of North Peak, the South Robertson Pasture laccolith rests on about 200 feet of the Mancos Shale, which in this locality dips southward. Beneath the shale the Dakota and Burro Canyon crop out; they overlie and form part of the sedimentary cover for the roof of the North Robertson Pasture laccolith. Thus, the South Robertson Pasture laccolith, locally at least, rests on the roof of the North Robertson Pasture laccolith.

Along the northeast edge of the South Robertson Pasture laccolith, the floor rests on Mancos strata which dip westward at about 30°. Hence it appears that the strata along both its north and northeast flanks were either already folded or being deformed when the laccolith was emplaced.

NORTH ROBERTSON PASTURE LACCOLITH

The northwest tip of East Mountain is formed by a partly denuded oval laccolith of porphyry known as the North Robertson Pasture laccolith (pl. 1). In gross aspect it is asymmetric and has moderately steep flanks on the west, north, and east merging to form a gentle crescent, convex to the northeast (pl. 2). In contrast, the south flank of the laccolith is straight, very steep, and marked by rock cliffs, rock slides, and boulder fields. Locally, elongate linear rock slides, their surfaces free of vegetation, extend downslope from the roof of the laccolith.

In plan view the North Robertson Pasture, South Robertson Pasture, and Corral laccoliths form a lobate pattern about the northwest end of the Abajo Peak feeder laccolith that suggests that all are related (fig. 20).

The North Robertson Pasture laccolith occupies most of secs. 21 and 22, T. 33 S., R. 22 E. It is about 1½ miles long, about 1⅓ miles wide, and probably was about 1,800 feet thick when emplaced (pl. 4; table 4). It is elongate to the northwest and, if related to the Abajo Peak laccolith, was probably emplaced about N. 40° W. from the distal end of that laccolith.

The North Robertson Pasture laccolith differs in one important aspect from the others around the margin of the Abajo Peak feeder laccolith. Whereas the other laccoliths rest on the Mancos Shale and presumably were capped by that unit, the North Robertson Pasture laccolith rests on the Morrison Formation, and has the Dakota and Burro Canyon as a sedimentary cover. Since emplacement of the laccolith, dissection has been severe, and the only evidence left of this former sandstone cover are hogbacks along the east and south flanks of the laccolith (pl. 1). These hogbacks extend unbroken to the edge of an extensive boulder field along the north flank of the laccolith. They reappear on the west flank of the laccolith but are not as well exposed. It seems likely that the hogbacks are concealed beneath the boulder field, for angular boulders of Dakota and Burro Canyon are in the boulder field.

The emplacement of the North Robertson Pasture laccolith in Morrison strata—even though adjacent laccoliths were emplaced in the Mancos Shale—may have resulted from the downward migration of magma, possibly along a fault. Thus, the magma from the feeder laccolith may have been insinuated into the basal part of the Mancos Shale as a thin sill. Near a point now occupied by North Peak the magma possibly moved into one or more fractures which guided it downward through both the basal strata of the Mancos and the Dakota and Burro Canyon. The extension of the fault that cuts across Indian Creek in secs. 19 and 20, T. 33 S., R. 22 E., could have acted as such a channelway (fig. 20). The fracture, or fractures, may have been partly closed in the structureless claystone beds of the Brushy Basin Member of the Morrison Formation. As a result, the downward progress of the magma was halted, and the magma was forced to move laterally below the sandstone. When this lateral migration was halted, the continued addition of magma resulted in a gradual dilation of the igneous body and a consequent arching of the Dakota and Burro Canyon.

Although evidence for such a downward transgression of the distal end of a laccolith has not been found in the Abajo Mountains area, good examples are known in the Ute Mountains. Here small curved apophyses of porphyry extend downward into older strata from the toe of an emplaced laccolith (F. N. Houser, oral communication, 1957). Specifically, the floor of the laccolith is in the Mancos Shale, but porphyry apophyses cut down through the shale and the Dakota Sandstone to end on top of the Burro Canyon Formation. As growth continued, these apophyses may well have expanded to form another laccolith emplaced in older strata.

Similar situations may have existed when the North Robertson Pasture laccolith and the laccoliths(?) that underlie the Corral and Spring Creek anticlines (fig. 20) were formed.

HORSEHEAD LACCOLITH

The northeast end of East Mountain is formed by the Horsehead laccolith (fig. 2*A*), one of two fringe laccoliths emplaced on the east flank of the Abajo Peak laccolith (fig. 20). Topographically the Horsehead laccolith appears, at its proximal end, as a single narrow-crested sinuous ridge, trending northeastward, and bounded by steep flanks (pl. 2). The northwest flank of the laccolith is delineated by the headwaters of Spring Creek, and its southeast flank is being dissected by North Creek and its tributaries. The steep slopes of the laccolithic flanks so common near its proximal end become more gentle near its distal end, and the very toe of the laccolith is a low blunt topographic prominence dissected into small elongate ridges and narrow steep-walled gullies.

The Horsehead laccolith occupies parts of secs. 25, 26, 35, and 36, T. 33 S., R. 22 E. (unsurveyed). It is about 1¾ miles long and 1⅓ miles wide, and is estimated to have been about 2,600 feet thick when emplaced (pl. 4; table 4). It seems to have been injected about N. 35° E. from the distal end of the Abajo Peak laccolith.

Most of the sedimentary strata that once covered the laccolith have been removed, and only remnants of this former cover are preserved near the proximal end of the laccolith and along its southeast flank. Near the proximal end, the Mancos Shale extends as an unbroken sheet across the northwest flank, onto the roof, and partly down the southeast flank. Dips on the flanks average about 18°; on the crest the strata are nearly horizontal. Locally the hummocky cover of the laccolith is marked by small knots of porphyry which protrude through and deform the Mancos Shale. In these localities the beds dip radially as much as 30° away from the intrusions.

The Mancos strata on the flanks of the laccolith are only partly altered. In contrast, the strata on the roof have been baked and indurated, and now appear as light-gray (*N* 7) thin-bedded, very fissile layers of hard shale which disintegrate into small angular fragments. Along the southeast flank of the laccolith a large wedge of the former Mancos Shale cover which dips about 22°

E. is preserved. The shale directly in contact with the porphyry has been baked and altered in a zone 3 to 6 feet thick. Above this zone, the beds are unchanged.

The floor of the laccolith is nowhere clearly exposed. Along the west valley wall of North Creek, however, the floor, near its proximal end, appears to overlie the Dakota and Burro Canyon, and then transgress upward onto basal Mancos Shale near its distal end. These Mancos strata extend east across North Creek and underlie the Pole Creek laccolith. Another poor exposure of the laccolithic floor is near the Forest Service road that leads to Spring Creek Lake (pl. 1). Here also the laccolith rests upon the basal part of the Mancos Shale.

The wedge of Mancos Shale preserved on the southeast flank of the Horsehead laccolith can be traced across North Creek to its contact with the Pole Creek laccolith. Poor exposures, dense vegetation, and thick colluvial deposits conceal the relations of that laccolith to the shale, but I think that the shale overlies at least part of the west flank of the Pole Creek laccolith.

No remnants of the Mancos Shale were found on the northwest flank of the Horsehead laccolith. Across Spring Creek, however, the Mancos Shale is well exposed under the South Robertson Pasture laccolith. These Mancos strata dip westward, and if one projects the dips upward to the east it is clear that the strata once continued across the roof of the Horsehead laccolith.

POLE CREEK LACCOLITH

The Pole Creek laccolith, along the east flank of East Mountain, occupies most of the NW¼ sec. 31, T. 33 S., R. 23 E. (fig. 2*A*). In plan view the laccolith is separated from the Horsehead laccolith to the west by the deep narrow canyon of North Creek (fig. 20). To the south it abuts the northeast flank of the Gold Queen laccolith and gives the impression that it is an extension to the northeast of that laccolith. It is, however, separate and distinct from the Gold Queen laccolith and probably is not related to it. The Pole Creek laccolith is provisionally classified as a discrete laccolith (table 4), but it may be a small lateral offshoot of the larger Horsehead laccolith to the west.

Much of the laccolith is exposed, except where concealed by small patches of Mancos Shale—remnants of a once extensive sedimentary cover (pl. 1). The general topographic shape of the exposed porphyry core suggests that the laccolith was about 1 mile long, 0.6 mile wide, and about 1,000 feet thick when emplaced (pl. 4; table 4). Its direction of emplacement is in doubt, for it is uncertain which, if any, of the adjacent laccoliths is the parent or feeder laccolith. If the Pole Creek laccolith is an offshoot of the Horsehead laccolith, it was emplaced about N. 63° E. from a point near the northeast toe of that laccolith; if it is a fringe laccolith of the Gold Queen laccolith, it was emplaced about N. 5° E. from the north flank of that laccolith.

Exposures are poor, but the laccolith probably rests partly on the Dakota and Burro Canyon and partly on the Mancos Shale. The laccolithic floor is exposed at its south edge where it overlies the sedimentary strata that mantle the north flank of the Gold Queen laccolith (p. 59–60). In this locality the Dakota and Burro Canyon, which form the roof of the Gold Queen laccolith, dip under the Pole Creek laccolith. Westward the floor of the Pole Creek laccolith rises and rests on Mancos Shale. These strata extend westward across North Creek and underlie the Horsehead laccolith. As noted above, the wedge of Mancos Shale on the east flank of the Horsehead laccolith extends east cross the North Creek where it may overlie a part of the west flank of the Pole Creek laccolith.

The Mancos remnants preserved on both the north and east flanks of the Pole Creek laccolith are further evidence that the Mancos Shale once covered the flanks and roof. It is suggested, therefore, that this laccolith was emplaced chiefly in the Mancos Shale and only locally on top of the Dakota and Burro Canyon.

The Pole Creek laccolith can also be traced westward across North Creek to its junction with the Horsehead laccolith. The continuity of the two laccoliths and their emplacement along the same stratigraphic horizon imply that the two laccoliths are related.

INFERRED LACCOLITH UNDER CORRAL ANTICLINE

Two blunt anticlines at the very north tip of East Mountain are thought to have cores of porphyry. The first, known as the Corral anticline, occupies parts of secs. 22 and 23, T. 33 S., R. 22 E. (unsurveyed; fig. 20). About 2 miles to the east is the center of the second anticline, referred to as the Spring Creek anticline, which covers most of secs. 13 and 23, T. 33 S., R. 22 E., and secs. 18 and 19, T. 33 S., R 23 E. Both anticlines are thought to be underlain by laccoliths and are here classified arbitrarily as discrete laccoliths, although they may be related to the Abajo Peak laccolith (table 4).

The Corral anticline is crudely circular, about three-fourths mile in diameter and 750 feet high; it is covered almost completely by the Dakota and Burro Canyon. Around the lower flanks of the anticline, remnants of the Mancos Shale crop out as small hogbacks partly concealed by pediment deposits. The top of the anticline is nearly flat; dips on the west, north, and east flanks range from 18° to 35°. On the south the anticline abuts part of what may be the distal end of the Abajo Peak feeder laccolith (pl. 2).

The sedimentary cover of the anticline has not been breached and consequently igneous rocks are not exposed. It is unknown which sedimentary strata were invaded by the igneous material, but analogy with the Gold Queen and other laccoliths to the south indicates that the laccolith likely was emplaced below the Dakota and Burro Canyon, possibly in the Brushy Basin Member of the Morrison Formation. In general, the continuity of the Corral anticline with what may be the toe of the Abajo Peak laccolith suggests that the laccolith under the Corral anticline may have formed in much the same manner as the North Robertson Pasture laccolith (p. 57).

INFERRED LACCOLITH UNDER SPRING CREEK ANTICLINE

The Spring Creek anticline occupies most of secs. 13 and 24, T. 33 S., R. 22 E., and secs. 18 and 19, T. 33 S., R. 23 E. (fig. 20). It appears as an isolated low hill about 1 mile northeast of the main mass of East Mountain (pl. 2). It is a crudely circular symmetrical anticline about 2½ miles in diameter and about 1,000 feet high. The Dakota and Burro Canyon are the dominant formations exposed. In the northeast part of the anticline, however, a small tributary of Spring Creek has breached the sandstone cap and exposed the Brushy Basin Member of the Morrison Formation. The top of the anticline is broad and almost flat, but the cap rock of the Dakota and Burro Canyon is flexed downward along the flanks; dips range from 3° to 40° on the north, east, and south.

Igneous rocks are not exposed, but it seems likely that the laccolith was emplaced in basal strata of the Brushy Basin Member of the Morrison Formation in much the same manner as the Gold Queen laccolith to the south. If a laccolith does, in fact, underlie the Spring Creek anticline, the difference between it and the Gold Queen laccolith would seem to be one of degree of dissection. Much of the sedimentary cover of the Gold Queen laccolith has been removed and the igneous core is exposed. In contrast, streams dissecting the Spring Creek anticline have cut through the cap of the Dakota and Burro Canyon, but have not, as yet, removed enough of the underlying Brushy Basin Member to expose the laccolith (fig. 21A).

The laccolith under the Spring Creek anticline has been arbitrarily classed as a discrete laccolith (table 4), although it could be interpreted either as a fringe laccolith of a deeply buried concealed feeder which has not been exposed by erosion, or as a fringe laccolith of the Abajo Peak laccolith but formed beyond the limits of most of the other fringe laccoliths.

GOLD QUEEN LACCOLITH

The Gold Queen laccolith, classified as a contiguous laccolith (table 4), occupies all or part of six sections, its major part being in sec. 1, T. 34 S., R. 22 E. (unsurveyed), and sec. 6, T. 34 S., R. 23 E. (figs. 2*A*, 20). It is about 2 miles in diameter and probably was about 1,500 feet thick when emplaced. It was injected wholly in the Morrison Formation on a trend of about N. 45° E. from the East Mountain stock.

The Gold Queen laccolith is one of the best examples of a partly denuded laccolith in the Abajo Mountains area; one-half to two-thirds of the laccolith is still covered by sedimentary rocks. Dissection has reduced what was once a blunt, even-surfaced symmetrical anticline, comparable to the Spring Creek anticline, to narrow-crested steep ridges and deep canyons. The anticline is still apparent, however; the steeply dipping adjacent sedimentary strata encircle the exposed igneous core.

On the north, the anticline, underlain by the Gold Queen laccolith, abuts the Pole Creek laccolith, and on the west it is continuous with the Abajo Peak laccolith.

The crest of the anticline is almost flat and is formed locally of remnants of the Dakota and Burro Canyon. Where the cap rock has been eroded from the upper flanks of the anticline, the underlying Brushy Basin Member of the Morrison Formation is exposed and forms intricately dissected slopes. The sandstone crops out again on the lower flanks of the anticline where it forms jagged serrated hogbacks on the north, east, and south sides. The outcrop pattern of the hogbacks reemphasizes the circular shape of the underlying laccolith. Dips on the upper flanks of the anticline average 10°; these steepen on the lower flanks and range from 21° to 60°. Away from the anticline the dips flatten rapidly and are as low as 4° about a mile to the east.

In a few places, the laccolith cuts across the sedimentary rocks. Along its north and east flanks the laccolith is overlain by claystone beds of the Brushy Basin Member of the Morrison, but the southeast flank, in sec. 7, T. 34 S., R. 23 E., cuts discordantly across younger strata, and is in contact with the Dakota and Burro Canyon. To the west, the porphyry cuts across the Dakota and Burro Canyon, and in sec. 12, T. 34 S., R. 22 E. (unsurveyed) the Mancos Shale is in contact with the roof of the laccolith.

The north flank of the laccolith is outlined by both the Morrison Formation and the Dakota and Burro Canyon which dip northward at about 24°. These beds pass beneath and underlie the Pole Creek laccolith. On the south flank of the Gold Queen laccolith, the Dakota and Burro Canyon dip below the South Creek laccolith. Thus, the Pole Creek laccolith to the north and the South Creek laccolith to the south rest on sedimentary beds which overlie the Gold Queen laccolith.

SOUTH CREEK LACCOLITH

The small South Creek laccolith, attached to the East Mountain stock, occupies the NE¼ sec. 13, T. 34 S., R. 22 E. (unsurveyed), and forms a blunt narrow crested porphyry ridge that projects southeast and is topographically lower than the hill formed by the parent stock (pl. 2). Gold Queen Gulch separates the north flank of the South Creek laccolith from the Gold Queen laccolith to the north, and Dickson Gulch separates the south flank from the South Peak laccolith (fig. 20).

The South Creek laccolith is about ¾ mile long, 6/10 mile wide, and probably was about 800 feet thick when emplaced (pl. 4; table 4). It extends S. 85° E. from the east end of the East Mountain stock. Its proximal end is indistinct for it merges with the shatter zone that encircles the East Mountain stock. Its distal end, however, is a well-delineated topographic prominence.

All that remains of the former sedimentary cover is a block of Mancos Shale that dips eastward at about 19° and is on the distal edge of the laccolith. Near the proximal end where the laccolith merges with the shatter zone, huge blocks of Mancos Shale and Dakota and Burro Canyon, tilted in all conceivable attitudes, mantle the south flank of the laccolith. These blocks have been mineralized in part by sulfides. Tailings from prospects dug in these remnants contain large amounts of pyrite.

The floor of the laccolith is poorly exposed but seems to rest on the basal strata of the Mancos Shale. The Mancos remnant on the flank and the beds of the Mancos below the floor indicate that the laccolith was intruded wholly into the Mancos Shale.

SOUTH PEAK LACCOLITH

The South Peak laccolith in secs. 13 and 24, T. 34 S., R. 22 E. (unsurveyed), is classed as a contiguous laccolith and is the second of the two feeder laccoliths attached to the East Mountain stock (fig. 20)—the first and major one being the Abajo Peak laccolith (p. 54). Around the east and south flanks of the South Peak laccolith are three small fringe laccoliths, the Dickson Creek laccolith on the northeast, the Verdure laccolith on the southeast, and the Arrowhead laccolith on the southwest (pl. 2).

In plan view the South Peak laccolith is a huge oval mass whose long axis is oriented to the southeast. Its roof, for most of its extent, is a narrow-crested sinuous hummocky ridge that is slightly higher than the hillock formed by the parent stock. The laccolithic flanks are steep and marked by broad shallow valleys separated by narrow linear ridges. Several of these ridges trend normal to the axis of the South Peak laccolith and join the fringe laccoliths. Consequently, they are interpreted as former feeders for the fringe laccoliths.

The South Peak laccolith is about 1½ miles long, ranges in width from about ½ mile at its proximal end to about 1⅓ miles at its distal end, and probably was about 1,600 feet thick when emplaced (pl. 4; table 4). It seems to have been injected S. 12° E. from the south edge of the East Mountain stock.

The laccolith is almost completely denuded. In a few places, however, along the west flank, small metamorphosed remnants of the Mancos Shale suggest that locally the Mancos formed the sedimentary cover. The floor of the laccolith is exposed only along the west flank where it rests on claystone beds of the Brushy Basin Member of the Morrison Formation. Farther east, the fringe laccoliths rest on the Dakota and Burro Canyon. It can be surmised, therefore, that the first surge of magma was emplaced below the Dakota and Burro Canyon. As the magma moved outward, it cut through younger beds until it reached the top of the Dakota and Burro Canyon; it then pushed its way below the Mancos Shale arching that unit.

DICKSON CREEK LACCOLITH

The Dickson Creek laccolith, in the S½ sec. 18, T. 34 S., R. 23 E. (fig. 20), is joined to the main mass of the South Peak laccolith by an elongate narrow, eastward-trending ridge of porphyry. The Dickson Creek laccolith is about 6/10 mile long by about 6/10 mile wide, and probably was about 400 feet thick when emplaced (pl. 4; table 4). It seems to have been emplaced about N. 80° E. from the middle of the east flank of the South Peak laccolith.

Remnants of the Mancos Shale are preserved on the crest; it may be inferred, therefore, that the Mancos once formed the sedimentary cover.

The floor of the laccolith is exposed along its north and east flanks. Along the north flank the floor rests on basal strata of the Mancos; eastward the floor cuts downward to older strata and near the southeast edge of the laccolith, the floor rests on the Dakota and Burro Canyon.

VERDURE LACCOLITH

The Verdure laccolith and the Dickson Creek laccolith to the north form a low broad porphyry bench around the east and south flanks of the South Peak laccolith (pl. 2).

Topographically, the Verdure laccolith in secs. 19 and 30, T. 34 S., R. 23 E., is distinct from both the South Peak and Dickson Creek laccoliths, although it is in igneous contact with both.

The Verdure laccolith is about ½ mile long, about 1⅓ miles wide, and was about 600 feet thick when emplaced (pl. 4; table 4). It was probably injected about S. 62° E. from the distal end of the South Peak laccolith (fig. 20).

Most of the sedimentary cover has been removed, and the denuded Verdure laccolith is mantled here and there by small remnants of Mancos Shale. The floor of the laccolith is exposed all along its distal (east) edge, where it rests on the Dakota and Burro Canyon. In the S½ sec. 19, T. 34 S., R. 23 E., dissection has cut through the laccolith and exposed the underlying Dakota and Burro Canyon.

Northward the floor of the Verdure laccolith is continuous with that of the Dickson Creek laccolith, which in this vicinity also rests on the Dakota and Burro Canyon.

The fact that the Dickson Creek and Verdure laccoliths have the same stratigraphic unit as a base, their continuity, and their common igneous contact with the South Peak laccolith imply that both were emplaced at about the same time and under similar conditions.

ARROWHEAD LACCOLITH

Porphyry exposures along both valley walls of Recapture Creek, in secs. 23 and 26, T. 34 S., R. 22 E. (unsurveyed), are interpreted as part of a laccolith that was cut in two by Recapture Creek. These exposures can be interpreted in other ways, but the general field relations are such that in my opinion they are best considered as parts of the same laccolith. This laccolith, known as the Arrowhead laccolith, probably was about 1 mile long, 1 mile wide, and about 1,000 feet thick when emplaced (pl. 4; table 4). It seems to have been injected about S. 37° W. from the southwest edge of the South Peak laccolith.

The Arrowhead laccolith is covered, near its proximal end, by the Dakota and Burro Canyon and, near its distal end, by the Brushy Basin Member. The floor of the laccolith, almost everywhere concealed by talus and thick vegetation, probably rests on the Brushy Basin Member of the Morrison Formation.

The proximal end of the Arrowhead laccolith may be in fault contact with the southwest toe of the South Peak laccolith. A wedge of Dakota and Burro Canyon, which overlies the Arrowhead laccolith, has been raised and tilted back against a remnant of the Mancos Shale preserved on the flank of the South Peak laccolith (pl. 1). This fault probably formed during the emplacement and consolidation of the Arrowhead and South Peak laccoliths.

KNOLL LACCOLITH

One of the contiguous laccoliths that encircle the East Mountain stock is the Knoll laccolith which occupies the SE¼ sec. 14 and the NE¼ sec. 23, T. 34 S., R. 22 E. (unsurveyed; fig. 20). It appears as a thin layer of porphyry that crops out along the west valley wall of Recapture Creek Talus and colluvium cover most of the outcrop and, together with a thick soil mantle, conceal many of the contacts. The laccolith probably is about ½ mile long by about ⅓ mile wide, and may have been as much as 300 feet thick when emplaced (pl. 4; table 4). It was probably injected about S. 55° W. from the southwest end of the East Mountain stock.

Near its distal end, the Knoll laccolith is covered by, and rests on, claystone beds of the Brushy Basin Member of the Morrison Formation. Its proximal end, however, is overlain by the Dakota and Burro Canyon, which here dip southwest about 25°.

An elongate exposure of porphyry in the north-central part of sec. 23, T. 34 S., R. 22 E. (unsurveyed), probably represents the exposed northwest flank of the Knoll laccolith. Its southeast flank has been eroded away by Recapture Creek.

The position of the Knoll laccolith suggests that it overlies a part of the east flank of the Camp Jackson laccolith which is in the Brushy Basin Member of the Morrison Formation.

CAMP JACKSON LACCOLITH

The bulk of the Camp Jackson laccolith is concealed beneath sedimentary strata in secs. 14, 15, 22, 23, 26, and 27 of T. 34 S., R. 22 E. (unsurveyed; fig. 20). Removal in a few places, chiefly in stream valleys, of part of the sedimentary cover has exposed the laccolith; elsewhere, dikes, sills, and small igneous bosses protrude through the cover and indicate the composition and texture of the buried laccolith.

The Camp Jackson laccolith was injected southwestward from the southwest tip of the East Mountain stock.

The north limit of the Camp Jackson laccolith is uncertain, but it may extend beneath the sedimentary strata that form the floor of the Jackson Ridge laccolith (pl. 1). The west edge of the anticline, underlain by the Camp Jackson laccolith, is delineated in part by Johnson Creek, and in part by a sinuous syncline which is followed by a segment of the Blue Mountain-North Creek mountain road. To the south the anticline ends against the North Verdure fault of the Verdure graben.

It is estimated that the Camp Jackson laccolith is about 2 miles long and about 1¼ miles wide, and was about 1,600 feet thick when emplaced (pl. 4; table 4). It was probably injected about S. 30° W. from the southwest edge of the East Mountain stock.

The laccolithic roof is not well exposed. Part, at the very distal end of the laccolith, may be represented by the porphyry exposures along and near the section line between secs. 15 and 22, T. 34 S., R. 22 E. (unsurveyed). Other exposures of the porphyry along the east flank of Cooley Gulch may also be part of the roof (pl. 1).

The small igneous outcrops along the west valley wall of Recapture Creek, in the center and near the south edge of sec. 23, T. 34 S., R. 22 E. (unsurveyed), are interpreted as small dikes or bosses connected to the buried laccolith. A similar interpretation probably applies to the porphyry exposure in the center of the S½ sec. 14, T. 34 S., R. 22 E. (unsurveyed; pl. 1).

All these outcrops are overlain by, or are in contact with, Morrison strata (Brushy Basin Member) and it seems likely, therefore, that the laccolith was emplaced in that unit. The laccolithic floor is nowhere exposed, but probably the laccolith was emplaced either below or on top of one of the lenticular sandstone beds of the Salt Wash Member of the Morrison Formation.

The general relations between the South Peak and Camp Jackson laccoliths are obscure. The parent magma of the South Peak laccolith must have been injected directly below the Dakota and Burro Canyon, whereas the Camp Jackson laccolith was emplaced in older strata, possibly the Morrison Formation. It appears, therefore, that the Camp Jackson laccolith undelies part of the South Peak laccolith.

WEST MOUNTAIN STOCK AND RELATED LACCOLITHS

The West Mountain stock is the second of the two known stocks in the Abajo Moutains area, the other being the East Mountain stock (p. 47). These stocks, which played such an important role in the igneous history of the area, are inconspicuous, and neither forms a prominent topographic landmark (pl. 2). The East Mountain stock is a small hill topographically lower than the crests formed on the Abajo Peak and South Peak laccoliths (fig. 2*A*). The West Mountain stock is even less striking for it merges with the undulatory crestline at the head of Dry Wash (fig. 2*B*).

In plan, the West Mountain stock appears as a crudely circular body about half a mile in diameter along the section line between secs. 7 and 18, T. 34 S., R. 22 E. (unsurveyed; fig. 20). Its actual size is unknown, because a dense stand of evergreens on its north flank and a thick colluvial cover on its south flank mask the margins.

The West Mountain stock consists largely of quartz diorite porphyry and a small amount of quartz diorite porphyry breccia. Most of the breccia exposures are on the east and west margins of the stock. Between these outcrops, the stock is composed of porphyry identical to the porphyry that forms the laccoliths. Most of the breccia exposures are small and merge imperceptibly at their margins, both laterally and vertically, into characteristic porphyry. In appearance and mode of outcrop these brecciated areas seem identical to similar exposures in the East Mountain stock.

The two stocks differ in degree of fracturing. Most of the East Mountain stock is cut by closely spaced fractures (p. 47–49), but the West Mountain stock is almost free of fractures. Locally, closely spaced fractures cut both the quartz diorite porphyry and the breccia of the West Mountain stock, but such fracture zones cannot be traced laterally for more than 50 feet and commonly are confined to irregularly shaped areas separated by broad expanses of unfractured porphyry. In general, the fractures in the West Mountain stock trend either N. 35° W. or about N. 65° E. This trend contrasts with that of the fracture patterns noted in the East Mountain stock, where one set of fractures trends N. 68° W. and the other N. 60° E.

The fractures in the West Mountain stock are filled with quartz and resemble the quartz-filled fractures in the East Mountain stock.

The fractured rocks in the West Mountain stock do not appear to have been as intensely altered as similar rocks in the East Mountain stock. Generally the alteration in the West Mountain stock shows merely as a lightening in color of the rocks to very light gray (*N* 8) from the original light gray (*N* 7). This color change contrasts with the dark yellowish orange (10*YR* 6/6) of the fractured and altered rocks in the East Mountain stock.

Only a few prospects are in the West Mountain stock, and these are chiefly in the fractured areas. In the tailings near these prospects, pyrite is the dominant sulfide.

The shatter zone about the West Mountain stock consists of chaotically jumbled blocks of sedimentary strata that have been intruded by minor igneous bodies. The boundaries of the shatter zone are drawn arbitrarily, because in many places the relations of this zone to the adjacent rocks are so vague and gradational that it is almost impossible to distinguish one from another. Sedimentary strata represented in the shatter zone include the Morrison Formation, the Dakota and Burro Canyon, and the Mancos Shale. Other units may be present but were not recognized.

The width of the shatter zone around the West Mountain stock ranges from about 500 feet on the north flank to about 2,000 feet on the east and southeast flanks.

A shatter zone, which can be traced all around the East Mountain stock, flanks the West Mountain stock only on the north, east, and south. On the west, the proximal edge of the Mount Linnaeus laccolith is attached to the stock and the shatter zone is missing. It is inferred that the Mount Linnaeus laccolith has cut through the shatter zone and concealed it (fig. 22).

Apparently the shatter zone is much like a sheath that encircles the stock and through which project laccoliths with different trends and at different altitudes, but all attached to the parent stock.

The shatter zone that partly encircles the West Mountain stock is analogous, in many respects, to the shatter zone about the East Mountain stock. This and other striking similarities between the stocks suggest that both were emplaced in much the same manner. Similar shatter zones encircle the stocks in the Henry Mountains (Hunt, 1953). The stocks in the La Sal Mountains (C. B. Hunt, oral communication, 1958), as well as those in the Ute Mountains (E. B. Ekren, oral communication, 1958), are encircled by very poorly developed shatter zones.

The West Mountain stock is encircled by five contiguous laccoliths (pl. 4; table 4): the Shay Ridge laccolith on the north, the Indian Creek laccolith on the northeast, the Dry Wash laccolith on the south, the Mount Linnaeus laccolith on the southwest, and the Allen Canyon laccolith on the west (pl. 2). All these, with the exception of the Mount Linnaeus laccolith, were emplaced in the Morrison Formation. The Mount Linnaeus laccolith was emplaced in the basal strata of the Mancos Shale.

SHAY RIDGE LACCOLITH

The Shay Ridge laccolith trends northward as a narrow-crested sinuous hummocky ridge that occupies the major part of secs. 6 and 7, T. 34 S., R. 22 E. (unsurveyed; fig. 20). Near its north end, the ridge narrows abruptly and steepens, and the sedimentary strata are tilted up around the toe of the laccolith.

The bulk of the laccolith is concealed beneath sedimentary strata, but on the basis of poor exposures it is estimated that the Shay Ridge laccolith is about 2¼ miles long and about 1 mile wide. Its thickness is unknown, for its floor is not exposed, but the laccolith is estimated to have been about 1,800 feet thick when emplaced (pl. 4; table 4).

The structural crest of the laccolith coincides with the topographic crest and bears about N. 20° E. for about a third of a mile from the north edge of the West Mountain stock. The trend then alters to about N. 15° W. for the remainder of the laccolith's length.

A large porphyry exposure in the center of sec. 6, T. 34 S., R. 22 E., is interpreted to be part of the roof and toe of the laccolith. Near its north end, the porphyry is in contact with the Salt Wash Member (fig. 22); consequently it is inferred that the laccolith was emplaced in the Morrison Formation, probably in the uppermost strata of the Salt Wash Member. Southward toward the proximal end of the laccolith, the porphyry cuts upward into younger strata and the laccolith underlies and arches the Dakota and Burro Canyon and the Mancos Shale. Most of the laccolith, however, is emplaced beneath the claystone beds of the Brushy Basin Member. Here and there along the crest, small knots of porphyry, which probably represent minor irregularities on the roof of the laccolith, protrude through the beds and fold them back.

The general limits of the Shay Ridge laccolith are uncertain. The east flank is concealed beneath the Brushy Basin Member. These strata dip eastward and pass beneath the Twin Peaks laccolith. Thus,

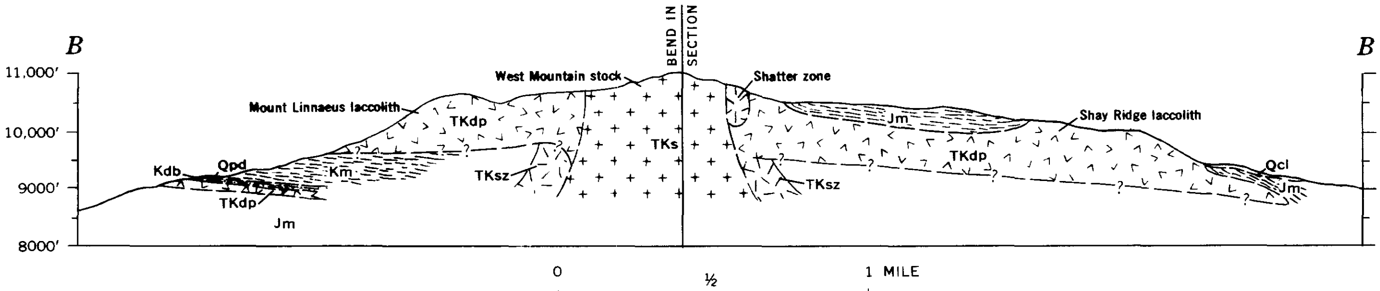


FIGURE 22.—Cross section of part of West Mountain showing the inferred relations of the West Mountain stock and its encircling shatter zone to two of its satellite laccoliths. Line of section shown on plate 1. (Qcl, colluvium; Qpd, pediment deposits; TKs, stock, quartz diorite porphyry and quartz diorite porphyry breccia; TKsz, shatter zone, TKdp, quartz diorite porphyry; Km, Mancos Shale, Kdb, Dakota and Burro Canyon; Jm, Morrison Formation.)

locally at least, the Shay Ridge laccolith underlies part of the Twin Peaks laccolith. The two small porphyry exposures in the NW¼ sec. 5, T. 34 S., R. 22 E. (unsurveyed), are probably local irregularities on the concealed laccolithic flank, whereas the large porphyry exposure in the north-central part of sec. 5 may be near the east edge of the laccolith's floor (pl. 1). The west flank of the laccolith is almost completely concealed beneath the Brushy Basin Member; the western limit of the laccolith, therefore, is unknown. A large dike in the NW¼ sec. 6, T. 34 S., R. 22 E. (unsurveyed) (pl. 1), may represent a protuberance on the northwest edge of the laccolith. If this dike is connected to the laccolith, it marks the northern limit of the Shay Ridge laccolith.

INDIAN CREEK LACCOLITH

The Indian Creek laccolith extends northeastward from the West Mountain stock as an elongate sinuous ridge that occupies most of secs. 5 and 8, T. 34 S., R. 22 E. (unsurveyed; fig. 20). About half of the ridge consists of a veneer of Morrison strata draped across the roof and flanks of the laccolith; the remainder of the ridge is formed by the denuded laccolith (pl. 1).

The Indian Creek laccolith is about 1½ miles long, about 1 mile wide, and probably was about 2,000 feet thick when emplaced (pl. 4; table 4). It seems to have been injected into Morrison strata about N. 42° E. from the northeast corner of the West Mountain stock. In plan view the laccolith is tongue shaped, but in longitudinal cross section it appears as a wedge having a narrow distal end and a very thick proximal end.

The cover of Morrison strata has been stripped from the flanks and crest at the proximal end of the laccolith, and all that remains is a large remnant on the southeast flank in the NW¼ sec. 8, T. 34 S., R. 22 E. (unsurveyed; pl. 1). The remnant is deformed but generally dips eastward from 13° to as much as 35°. Protruding through the remnant are two small igneous bosses that arch the adjacent strata and that are interpreted as minor bulges on the laccolith's flanks.

The distal end of the laccolith is concealed beneath strata tentatively correlated with the Salt Wash Member of the Morrison Formation. On the southeast flank these strata dip as much as 60° SE. In the center of the S½ sec. 8, T. 34 S., R. 22 E. (unsurveyed), the flank of the laccolith is overlain by younger strata that include the Brushy Basin Member of the Morrison Formation, the Dakota and Burro Canyon, and a small patch of the Mancos Shale—all preserved as a small topographic high. Locally the Morrison strata along the southeast flank of the laccolith are penetrated by small porphyry bosses. Four of these bosses are exposed near the center of sec. 8, T. 34 S., R. 22 E. (unsurveyed). Near the very toe of the laccolith the Morrison cover has been breached and the roof of the laccolith is exposed (pl. 1).

The floor of the laccolith is nowhere exposed, but is thought to rest on Morrison strata.

The west edge of the laccolith is concealed beneath Morrison strata, but it may be continuous with the east edge of the Shay Ridge laccolith. Possibly the juncture between the two laccoliths is along the deep narrow canyon of Bear Creek. The southeast flank of the Indian Creek laccolith probably ends against the Indian Creek fault.

DRY WASH LACCOLITH

The Dry Wash laccolith, a blunt igneous body that extends southward from the West Mountain stock, occupies the SE¼ sec. 18, T. 34 S., R. 22 E. (unsurveyed; fig. 20). Poor exposures and a thick colluvial cover conceal its shape, and I am uncertain, therefore, whether it is properly classified as a laccolith. Dissection has been severe, and for much of its extent the laccolith is divided into two parts, each segment now appearing as a thick porphyry exposure along the valley walls of Dry Wash. Most of the center of the laccolith has been removed.

The laccolith probably was about ½ mile long, about ½ mile wide, and about 600 feet thick when emplaced (pl. 4; table 4). Possibly it was injected about S. 18° E. from the south edge of the West Mountain stock. I estimate that since its emplacement about half of the laccolith has been eroded away.

Most of the laccolith seems to have been emplaced in Brushy Basin strata about 100 feet below the Dakota and Burro Canyon. At its distal end, the laccolith has split into thin sills intercalated in Triassic and Jurassic strata. In plan view, the reconstructed Dry Wash laccolith has a tongue-shaped outline similar to the other laccoliths; in longitudinal section, however, it resembles an open hand—the heel of the laccolith representing the palm of the hand, and the various sills representing the spread fingers.

On the east valley wall of Dry Wash the proximal end of the laccolith underlies strata tentatively correlated with the Brushy Basin Member of the Morrison Formation. In sharp contrast the laccolithic roof, exposed along the west valley wall of Dry Wash, underlies a wedge of the Mancos Shale.

The sills at the distal end of the laccolith are poorly exposed. Three main sills have been distinguished, two of which are emplaced chiefly in the Salt Wash

Member of the Morrison Formation. The third and lowest sill is a thick blunt body that intrudes sedimentary strata that range from the Summerville Formation (Jurassic) to the Chinle Formation (Triassic).

The Dry Wash laccolith is underlain in part by the claystone beds of the Brushy Basin Member of the Morrison Formation.

In the center of sec. 18, T. 34 S., R. 22 E. (unsurveyed), a part of the laccolith is overlain by, and is in contact with, the Mount Linnaeus laccolith. A short distance away, the two laccoliths are separated by a wedge of Mancos Shale that mantles the west edge of the roof of the Dry Wash laccolith. These same Mancos strata dip westward; they pass below and underlie the Mount Linnaeus laccolith (pl. 1). The Mount Linnaeus fault (p. 76), which ends along the west distal edge of the Dry Wash laccolith, was formed before the laccolith was emplaced, and therefore, probably determined the position of the west flank of the laccolith. In essence, the fault plane is reflected by the linearity of part of the west flank of the laccolith. Further, an elongate, nearly vertical porphyry dike, now exposed in the NW¼ sec. 19, T. 34 S., R. 22 E. (unsurveyed), is collinear with the fault. The field relations imply that the north tip of the dike is in buried contact with the distal end of the Dry Wash laccolith (pl. 1).

It seems likely that fault, dike, and laccolith are all related. Possibly the fault was formed first. Magma then moved into the channelway to form the dike and subsequently formed the sills that mark the distal edge of the laccolith. The lateral movement of the magma to the west may have been halted by the gouge along the Mount Linnaeus fault.

MOUNT LINNAEUS LACCOLITH

The Mount Linnaeus laccolith appears as a mass of porphyry perched high above the present stream bottoms and dominates the south part of West Mountain (fig. 2*B*). The laccolith occupies part of sec. 13, T. 34 S., R. 21 E. (unsurveyed), and part of sec. 18, T. 34 S., R. 22 E. (unsurveyed; fig. 20). In plan view the laccolith is crudely circular, about ¾ mile long, about 1 mile wide, and probably was about 1,200 feet thick when emplaced (pl. 4; table 4). It seems to have been injected about S. 35° W. from the West Mountain stock.

The laccolith has been completely denuded and no remnants of the former sedimentary cover were found. For most of its extent, the laccolith rests on the Mancos Shale, although its northwest corner is underlain by the Brushy Basin Member of the Morrison Formation. It seems likely that the laccolith was injected chiefly into basal strata of the Mancos, and that these once covered it.

The strata that underlie the Mount Linnaeus laccolith are deformed into an elongate syncline whose axis coincides with that of the laccolith. The strata that form the east side of the syncline end either against the Dry Wash fault or locally rest on the roof of the Dry Wash laccolith; similarly the strata that form the west side of the syncline rest on the roof of the Allen Canyon laccolith. The strata that underlie the Mount Linnaeus laccolith, therefore, overlie the Dry Wash laccolith on the east and the Allen Canyon laccolith on the west.

It is unknown whether the syncline was formed after or before the Mount Linnaeus laccolith was emplaced; in my opinion it antedated the laccolith. A possible sequence is the emplacement of the Dry Wash and Allen Canyon laccoliths first, probably synchronously, chiefly in Morrison strata. Between these laccoliths, the overlying strata were deformed into a broad shallow syncline. At some stage, the magma that formed the Dry Wash and Allen Canyon laccoliths broke through the overlying sedimentary beds and moved into basal strata of the Mancos, its lateral course determined by the synclinal axis. Eventually the lateral migration of the magma was halted, and the Mount Linnaeus laccolith was formed by continued addition of the magma.

That another igneous body of indeterminate size and shape, possibly a laccolith, may be concealed beneath the strata that underlie the Mount Linnaeus laccolith is suggested by isolated porphyry dikes, sills, and small bosses that protrude through Morrison and older strata. These minor intrusions are probably attached to the buried body, and their outcrop pattern may reflect the shape of that mass. The intrusions include two sills: one in the W½ of sec. 13, T. 34 S., R. 21 E. (unsurveyed; pl. 1), protruding through Morrison strata, and the other in the SW¼ of the same section, cropping out below the Dakota and Burro Canyon. An elongate dike and sill in the center of the E½ sec. 23, T. 34 S., R. 21 E. (unsurveyed), may be near the distal edge of the buried body. The dike extends from the base of the Morrison Formation to the base of the Entrada Sandstone where it passes into a sill. The south flank of the buried body may be outlined in the NW¼ sec. 19, T. 34 S., R. 22 E. (unsurveyed), by a small sill emplaced in the Summerville Formation and by a small igneous boss near the north edge of this same section.

ALLEN CANYON LACCOLITH

The Allen Canyon laccolith, occupying parts of secs. 11, 12, 13, and 14, T. 34 S., R. 21 E. (unsurveyed), appears as an elongate porphyry ridge separated from the Mount Linnaeus laccolith by the narrow and deep Allen Canyon (pl. 2).

The Allen Canyon laccolith has been classed as a contiguous laccolith attached to the West Mountain stock. The proximal part of the laccolith, however, is still concealed beneath the strata that underlie the Mount Linnaeus laccolith (fig. 23); consequently only the distal end is exposed. The Allen Canyon laccolith is estimated to be about 1½ miles long, about ½ mile wide, and to have been about 600 feet thick when emplaced. It seems to have been injected about N. 84° W. from the west edge of the parent stock (table 4).

Although most of the sedimentary cover has been removed from its distal end, outcrops on the north flank of the laccoliths indicate that it was probably emplaced in uppermost Morrison strata. Locally, as in the SW¼ sec. 12, T. 34 S., R. 21 E. (unsurveyed), the laccolith is overlain by the Dakota and Burro Canyon, but for most of its extent it is mantled by the claystone beds of the Brushy Basin Member. The floor of the laccolith probably rests on the same member, but rock slides, boulder fields, and colluvium formed on the laccolith's south flank conceal most of the exposures and make it difficult to determine the relationships.

JOHNSON CREEK STOCK(?) AND RELATED LACCOLITHS

The Johnson Creek dome in the SW¼ T. 34 S., R. 22 E. (unsurveyed; pl. 1) is one of the major structural elements in the southern part of the Abajo Mountains area. I think it represents the near-surface emplacement of a large igneous body, here tentatively classified as a stock (or bysmalith) and named the Johnson Creek stock(?). Although the stock(?) is not exposed, the laccoliths intercalated in the strata that form the dome suggest its composition, texture, and general location (fig. 24).

The center of the dome is about 4½ miles southwest of the exposed East Mountain stock and about 2 miles southeast of the West Mountain stock. Three of the four stocks, therefore, are in the southern part of the Abajo Mountains area (pl. 2).

The strata that form the east edge of the dome are moderately well exposed, chiefly in the valley walls of Johnson Creek and its tributaries. Elsewhere, the strata are concealed beneath dense vegetation and a veneer of scree.

The dome is about 3 miles in diameter. Parts have been truncated by inconspicuous bounding faults which lack topographic expression. Thus, the south flank of the dome is cut by the Dry Wash fault (pl. 1) which curves to the northeast and at its east end dies out along the east flank of the dome (p. 75). For the greater part of its length the Dry Wash fault is along a ridge. The west flank of the dome is truncated by the northwestward-trending Mount Linnaeus fault (pl. 1). This fault, exposed, on both valley walls of Dry Wash, ends at the west distal edge of the Dry Wash laccolith (p. 76). A third fault may have cut across the north flank of the dome and served as the channelway for the magma that formed the Porcupine laccolith (fig. 24; p. 70). Possibly this fault was an eastward extension of the Indian Creek fault.

Sedimentary strata in the dome range in age from Permian (Cutler Formation) to Jurassic (Morrison Formation), that is, almost a complete stratigraphic section of all units found in the Abajo Mountains area is exposed: Only the Dakota and Burro Canyon and the Mancos Shale are missing.

The Johnson Creek dome, almost surrounded by faults, is probably underlain by a stock whose sides are nearly vertical—an incipient bysmalith, in a sense. Had the igneous mass continued to rise, it seems likely

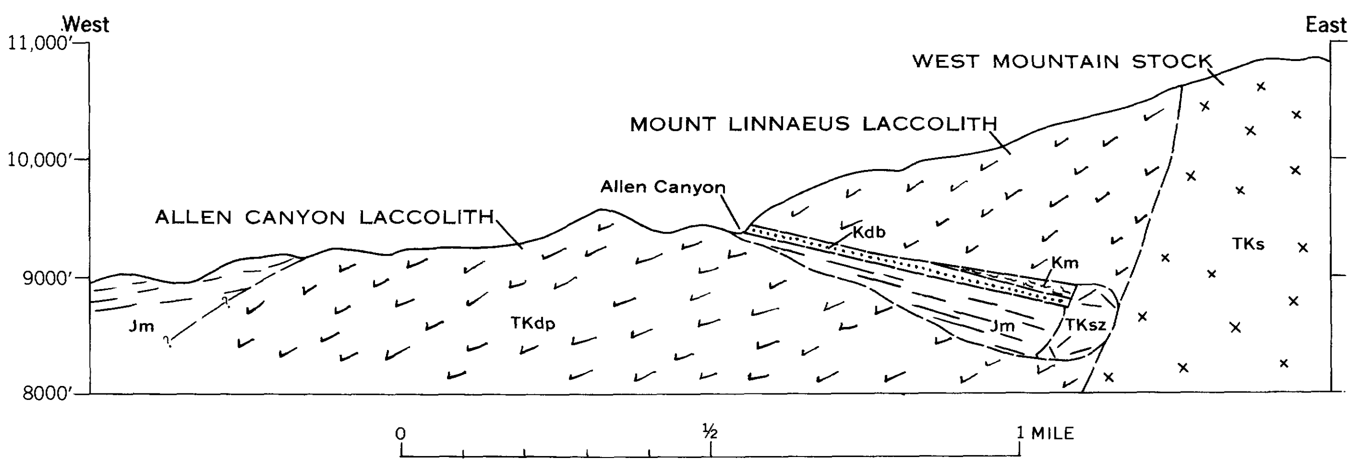


FIGURE 23.—Cross section showing possible relations between the Mount Linnaeus and Allen Canyon laccoliths. (TKs, stock, quartz diorite porphyry, and quartz diorite porphyry breccia; TKsz, shatter zone; TKdp, quartz diorite porphyry; Km, Mancos Shale; Kdb, Dakota and Burro Canyon; Jm, Morrison Formation.)

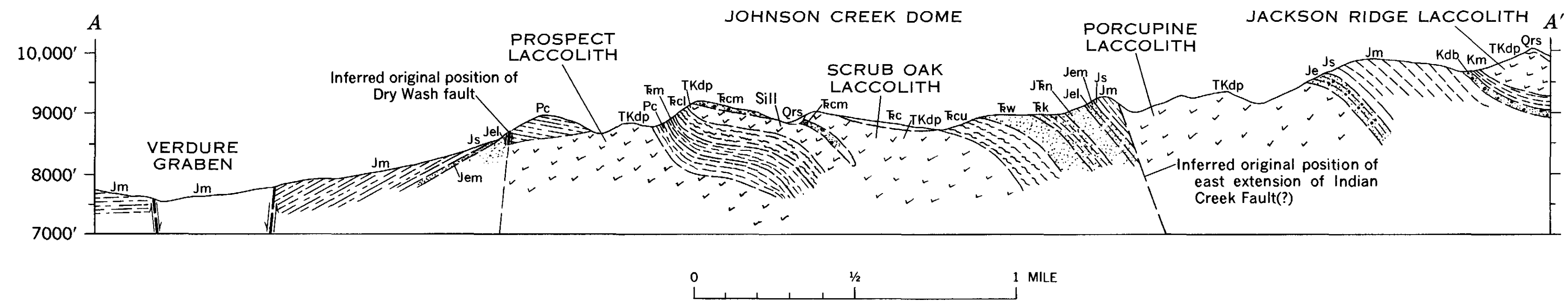


FIGURE 24.—Section across the Johnson Creek dome showing possible relations of various laccoliths to the invaded strata. Line of section shown on plate 1. (Qrs, rockslides and boulder fields; TKdp, quartz diorite porphyry; Km, Mancos Shale; Kdb, Dakota and Burro Canyon; Jm, Morrison Formation Js, Summerville Formation; Je, Entrada Sandstone, undifferentiated; Jem, Moab Sandstone Member of Entrada Sandstone; Jel, lower unit of Entrada Sandstone; JꞦn, Navajo Sandstone; Ꞧk, Kayenta Formation; Ꞧw, Wingate Sandstone, Ꞧcu, upper unnamed member of Chinle Formation; Ꞧcm, Moss Back Member of Chinle Formation; Ꞧcl, lower unnamed member of Chinle Formation; Ꞧc, Chinle Formation, undifferentiated; Ꞧm, Moenkopi Formation; Pc, Cutler Formation.)

that the overlying layers of sedimentary strata would have been thrust upward, and well-defined faults formed all around the raised plug. The final result would have been a bysmalith.

I suggest the following emplacement sequence: As the Johnson Creek stock (?) was emplaced, it arched the overlying strata to form the Johnson Creek dome, but for some reason the stock(?) did not reach the same altitude as the East and the West Mountain stocks. During this episode the strata overlying the stock were broken by three bordering faults, (a) the Dry Wash (p. 75), (b) the Mount Linnaeus (p. 76), and (c) the eastward extension(?) of the Indian Creek fault (p. 76). During the ascent of the stock(?), and when it was halted, thin sheets of magma were intruded into the overlying arched strata of the dome. Where the invading magma came in contact with one of the preexisting faults, the magma moved vertically up this new channelway, and then at favorable sites spread laterally to form sills that in time expanded to form laccoliths. Locally the lateral spread of magma was halted along a fault. Once halted, the addition of more magma caused dilation of the sheet to form a laccolith, one of whose sides was determined by, and coincides with, a fault plane.

At least three, and possibly five, laccoliths are intercalated in the strata that form the dome (fig. 20; table 4). The uncertainty about the number stems from the vague relations of those laccoliths formed at the very outer margins of the dome. Each laccolith is interpreted as being a contiguous laccolith attached to the Johnson Creek stock(?). The Prospect laccolith, exposed along the southwest flank of the dome, is almost completely encircled by strata of the Cutler Formation. The Scrub Oak laccolith, near the center of the dome, is emplaced wholly in the Chinle Formation. It rests on the Moss Back Member and is covered by the red siltstone beds of the upper member of the Chinle. The Porcupine laccolith crops out along the north flank of the dome, and it rests on strata of both the Summerville and Morrison Formations. Units tentatively assigned to the Moab Sandstone Member of the Entrada overlie the laccolith (fig. 24). The Ridge laccolith both rests on and is overlain by Morrison strata. The Viewpoint laccolith, exposed along the northeast flank of the dome, is thought to be emplaced wholly in the Morrison Formation.

PROSPECT LACCOLITH

The Prospect laccolith, along the southwest flank of the Johnson Creek dome, crops out at the head of a small tributary to Johnson Creek (fig. 20). Headward erosion by the tributary has removed some of the sedimentary cover and exposed a small part of the laccolith which has been dissected into rounded ridges and steep-walled narrow valleys. The laccolith underlies parts of secs. 19, 20, 29, and 30, T. 34 S., R. 22 E. (unsurveyed); the exposed roof is at the junction of the four sections.

Most of the laccolith is still concealed beneath sedimentary strata, but, if it is assumed that the Johnson Creek stock(?) is emplaced near the center of the dome, it can be estimated that the Prospect laccolith is about ¾ mile long, about 1⅓ miles wide, and possibly was about 1,400 feet thick when emplaced (pl. 4; table 4). It probably was emplaced about S. 50° W. from the southwest tip of the concealed stock(?).

The laccolith's west flank is unusually straight and is collinear with the Mount Linnaeus fault (pl. 1). The absence of both fault breccia and gouge along this flank suggests that the fault was in existence before the laccolith was emplaced. If the fault did antedate the laccolith, as I believe, the lateral spread of the magma responsible for the Prospect laccolith was probably halted along the Mount Linnaeus fault. As the laccolith formed, its west flank, coincident with the fault plane, was determined by (and now reflects) the straightness of that plane.

Additional evidence supports this concept. The elongate dike in the center of the N½ sec. 19, T. 34 S., R. 22 E. (unsurveyed), is collinear with the fault and, inasmuch as neither fault breccia nor gouge were noted along the dike, it seems likely that the fault was in exsitence before the dike was emplaced. Possibly the magma that formed the dike came from the West Mountain stock (pl. 1), but the magma that formed the Prospect laccolith came from the buried Johnson Creek stock(?).

The south edge of the Prospect laccolith abuts the Dry Wash fault in much the same manner as its west edge abuts the Mount Linnaeus fault. In neither locality was fault breccia or fault gouge noted. The Dry Wash fault probably also was formed before the laccolith was emplaced.

Possibly the two faults were formed synchronously during the upward thrust of the buried Johnson Creek stock(?). Even as they formed, or shortly afterward, magma from one or more sources used one or both faults as channelways. Locally where the faults were effective barriers to the lateral progress of the magma, the Prospect laccolith was formed.

In the SW¼ sec. 20, T. 34 S., R. 22 E. (unsurveyed), the contact between the laccolith and the overlying Cutler strata is marked by such copper minerals as chalcopyrite, azurite, malachite, and possibly chalcocite, as well as by pyrite. Most of these minerals coat joint planes in the sedimentary strata, although locally distinct grains are in the porphyry and form a zone 2 to 6 inches thick just below the contact. A small prospect has been dug along the roof of the laccolith near the north edge of this exposure.

SCRUB OAK LACCOLITH

The Scrub Oak laccolith, one of the best exposed laccoliths in the Abajo Mountains area (fig. 20), crops out in the center and SE¼ sec. 20, T. 34 S., R. 22 E. (unsurveyed), as a hummocky oval hill oriented to the northwest (pl. 2). The roof and flanks of the laccolith are partly concealed beneath vegetation and debris, but in places, especially where the laccolith is in contact with the overlying and underlying strata, exposures are good, and the general outline of the laccolith is easily delineated.

The southwest edge of the laccolith has been truncated by a major tributary of Johnson Creek, and this part of the laccolith now is perched about 100 feet above the stream bottom. A smaller tributary has partly uncovered the northeast flank; here, however, dissection has not been as deep, and the floor of the laccolith is exposed locally along the stream bottom.

The Scrub Oak laccolith is near the center of the Johnson Creek dome, and probably overlies at least part of the parent Johnson Creek stock(?). The laccolith is estimated to be about ¾ mile wide, and to range in length from about ⅕ to about ½ mile. It may have been about 600 feet thick when emplaced (pl. 4; table 4). It probably was extruded in a S. 50° W. direction from the tip of the Johnson Creek stock(?).

Most of the sedimentary cover has been removed and the laccolith now appears as a porphyry cap. Along its north and east edges, thin remnants of the former Chinle cover are still preserved as deep reddish-brown patches which contrast with the light gray of the underlying porphyry. The laccolith rests on the Moss Back Member of the Chinle Formation, which crops out along the southwest flank of the laccolith as a steep escarpment, partly concealed by boulder fields.

Near the center of the E½ sec. 20, T. 34 S., R. 22 E. (unsurveyed; pl. 1), the contact between the porphyry and the overlying Chinle strata is near vertical, the porphyry having crosscut the Chinle. The Chinle strata have been baked to form an altered zone about 2 feet wide. The only significant change in the porphyry is a chilled zone about 6 inches wide. About 100 feet farther west (closer to the main mass of the laccolith), the laccolithic floor is concealed, but the laccolithic roof concordantly underlies the sedimentary strata.

Locally, thin elongate striae, very similar to glacial striae, are exposed on the roof. Commonly these are about 8 inches long and about ⅛ to ¼ inch apart. They trend about S. 30° W., and form a narrow zone next to the edge of the sedimentary cover. Probably striae similar to these once covered the roof of the laccolith, but most have since been destroyed by erosion. Only those striae recently exposed are preserved. Similar striae have been found on roofs of laccoliths exposed in the Henry Mountains, and C. B. Hunt (oral communication, 1957) has suggested that they represent a minor shift of the magma just before it crystallized.

A porphyry sill about 60 feet thick underlies the Moss Back Member, and adds a further complexity. The sill has been cut into two parts by the same tributary that dissected the southwest edge of the Scrub Oak laccolith. One part of the sill underlies the Moss Back Member on which the Scrub Oak laccolith rests. The other part is exposed as a hummocky upland surface west of the Scrub Oak laccolith. Here remnants of Moss Back, still preserved on parts of the sill, appear as broad flat-topped benches; one is in the NE¼ sec. 29, and the other is in the SW¼ sec. 20, both sections in T. 34 S., R. 22 E. (unsurveyed; pl. 1).

Probably the sill and the laccolith are contiguous near their proximal ends (fig. 24), and both may have been formed synchronously—the magma moving laterally directly above and below the Moss Back Member. Possibly the magma on top of the Moss Back Member was able to expand and form a laccolith, whereas the magma below the Moss Back Member, unable to lift the combined weight of the sandstone and the magma, may have chilled, crystallized, and remained a sill.

PORCUPINE LACCOLITH

The Porcupine laccolith, on the north flank of the Johnson Creek dome, occupies parts of secs. 16 and 17, T. 34 S., R. 22 E. (unsurveyed; fig. 20), and appears as a dissected mass of porphyry overlain and underlain by sedimentary strata. Much of the sedimentary cover has been removed by an unnamed tributary of Johnson Creek, which has also cut a deep valley through the laccolith (pl. 1). North of the tributary, part of the laccolith is poorly exposed as broad rounded slopes separated by deep narrow ravines. The remainder of the laccolith, chiefly a segment of the base, is preserved south of the tributary as a steep valley wall.

The laccolith is about 1⅓ miles long and about ¾ mile wide. Its original thickness is uncertain but it may have been as much as 2,600 feet thick (pl. 4; table 4).

For much of its extent, the laccolith rests on strata of both the Summerville and Morrison Formations (pl. 1). Thus, the western part of the laccolith is underlain by Summerville strata. Eastward the floor extends upward to younger strata, and rests on one of the lower sandstone beds of the Salt Wash Member of the Morrison Formation. The roof of the laccolith is concealed beneath sedimentary strata that are older than the strata which underlie the laccolith—a most unusual situation, for generally a laccolith is overlain by strata younger than those which underlie it. The laccolith is covered by sandstone beds that cannot be differentiated but that can be correlated with both the lower unit of the Entrada Sandstone and the Moab Tongue of the Entrada Sandstone. Overlying these sandstone beds is a complete unbroken sequence of the Summerville Formation—the unit that elsewhere underlies part of the laccolith.

The unusual relations of the surrounding sedimentary strata to the laccolith can be explained in various ways. One explanation, which I favor, is that the laccolith was formed by magma intruded along an inferred, nearly vertical fault plane. Diagrammatic cross sections to illustrate how such a preexisting fault plane could localize a laccolith are shown in figure 25*A*. An alternative explanation is offered in figure 25*B*. Here also the Porcupine laccolith is intruded along a fault plane, but one that was formed during the emplacement of the laccolith.

Whichever interpretation is correct, it seems likely that the magma was guided, in large measure, by one or more faults. The straight west edge of the Porcupine laccolith (center sec. 17, T. 34 S., R. 22 E., unsurveyed) suggests some form of control. As this contact between the porphyry and Morrison strata is traced northward, the porphyry continues as a thin dike (center sec. 17, T. 34 S., R. 22 E., unsurveyed) that follows the Indian Creek fault (pl. 1). Inasmuch as neither fault breccia nor gouge was noted along the contact between the dike or laccolith and the adjacent sedimentary rocks, the inference is justified that a fault was in existence before these igneous bodies were emplaced.

Similarly, the linear south flank of the Porcupine laccolith may reflect a former fault through secs. 16 and 17, T. 34 S., R. 22 E. (unsurveyed; pl. 1). A small fault, in the SE¼ sec. 16, T. 34 S., R. 22 E. (unsurveyed), extends northeastward from the east flank of the Porcupine laccolith. Possibly this small fault

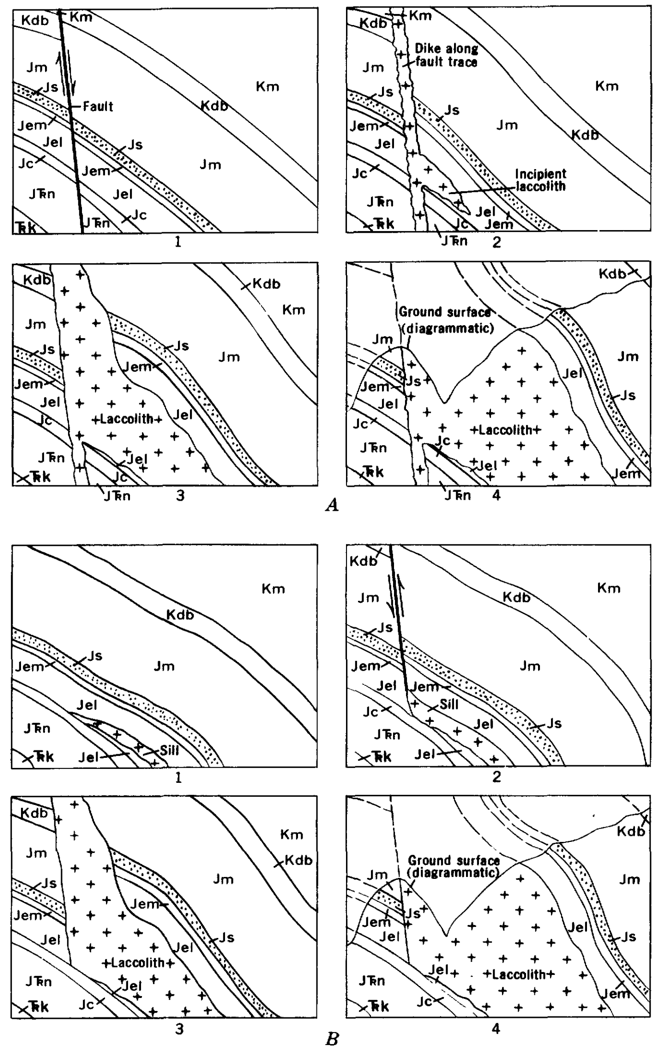


FIGURE 25.—Two hypotheses to explain the formation of the Porcupine laccolith. (For clarity, dots have been placed in the unit representing the Summerville.) (₮k, Kayenta Formation; J₮n, Navajo Sandstone; Jc, Carmel Formation; Jel, lower unit of Entrada Sandstone; Jem, Moab Sandstone Member of the Entrada Sandstone; Js, Summerville Formation; Jm, Morrison Formation; Kdb, Dakota and Burro Canyon; Km, Mancos Shale.)

A, Four idealized cross sections illustrating the formation of the Porcupine laccolith along a preexisting fault plane:

1. Strata displaced by high-angle fault, possibly an eastern extension of the Indian Creek fault.
2. Magma moves up along the fault plane and a small sill or incipient laccolith is formed in the lower unit of the Entrada Sandstone (Jel).
3. Continued addition of magma arches and displaces overlying strata.
4. Erosion of the emplaced laccolith. Younger strata (Morrison Formation) directly underlie the laccolith, and older strata (Entrada Sandstone) directly overlie it.

B, Four idealized cross sections illustrating the formation of the Porcupine laccolith as the result of the expansion of a sill:

1. Magma is intruded at the base of the Entrada Sandstone to form a thin sill.
2. As the magma increases, the overlying strata are faulted and raised.
3. Magma moves up the newly formed fault as the strata overlying the incipient laccolith are arched and further elevated.
4. Erosion of the emplaced laccolith. Younger strata (Morrison Formation) directly underlie the laccolith, and older Strata (Entrada Sandstone) directly overlie it.

is a remnant of the inferred fault that determined the linearity of the south and west flanks of the Porcupine laccolith. If so, this larger fault truncated the north flank of the Johnson Creek dome in much the same fashion as the Mount Linnaeus fault cuts the west flank, and the Dry Wash fault cuts the south flank. The western extension of this inferred fault may be the Indian Creek fault in sec. 17, T. 34 S., R. 22 E. (unsurveyed).

The source of the magma that formed the Porcupine laccolith is unknown. The magma may have come from the East Mountain stock, but I believe that it was derived from the concealed Johnson Creek stock(?). The inferred fault plane, however, is interposed between the Porcupine laccolith and the Johnson Creek stock(?). Possibly the stock(?) was intersected by the fault(?), or the magma may have moved along a concealed conduit to its intersection with the fault.

RIDGE LACCOLITH

The Ridge laccolith, one of the smaller laccoliths exposed in the Abajo Mountains area (fig. 20), occupies about a tenth of a square mile in the center of the N½ sec. 16, T. 34 S., R. 22 E. (unsurveyed). It appears as a narrow-crested ridge flanked by steep slopes (pl. 1).

The laccolith is estimated to be about ½ mile wide and ½ mile long, and probably was about 800 feet thick when emplaced (pl. 4; table 4).

The laccolith may have been drived from the Johnson Creek stock(?). If so, it was probably fed by an elongate buried conduit trending N. 30° E. from the concealed stock(?). Or it may have been formed by magma supplied by a feeder now concealed beneath a boulder field in the center of the SE¼ sec. 16, T. 34 S., R. 22 E. (unsurveyed; pl. 1).

The Ridge laccolith was emplaced wholly in Morrison strata, part of which overlie the north flank of the Porcupine laccolith (pl. 1). Dissection has been extensive, and most of the strata that concealed the Ridge laccolith have been removed, leaving only the southeast flank of the laccolith still hidden beneath sedimentary rocks. Here the Morrison strata dip southeastward and pass below the Viewpoint laccolith.

VIEWPOINT LACCOLITH

The Viewpoint laccolith, along the northeast flank of the Johnson Creek dome, is a porphyry mass that forms a narrow-crested ridge which slopes steeply down to the floor of Johnson Creek (pl. 2). The highest part of the exposed laccolith, at a viewpoint on the Blue Mountain-North Creek mountain road, is the laccolithic floor (pl. 1), which is inclined about 35° SE.

The laccolith occupies about two-tenths of a square mile along the section line between secs. 15 and 16, T. 34 S., R. 22 E. (unsurveyed). It is estimated to be about ¼ mile long and 1/10 mile wide; it was probably about 400 feet thick when emplaced (pl. 4; table 4).

Although erosion has removed the sedimentary cover, it seems probable that the Viewpoint laccolith was emplaced chiefly in Morrison strata. The laccolith rests partly on Morrison strata and partly on undifferentiated strata assigned to the Jurassic. Exposures are so poor that it is impossible to distinguish the units; they may range from the Summerville Formation to the Navajo Sandstone.

A fault (p. 70) in the SE¼ sec 16, T. 34 S., R. 22 E. (unsurveyed), extends to the southwest flank of the laccolith. Although exposures are poor and the fault plane is not exposed, I believe the fault passes beneath the laccolith, for the porphyry has not been offset. If the fault is below the laccolith, it must have been formed before the laccolith was emplaced and may, therefore, be related to the inferred fault that determined the location of the Porcupine laccolith (p. 70.)

The source and the direction of emplacement of the Viewpoint laccolith are unknown. It may be related to the Johnson Creek stock(?), or it may represent the very distal end of the Camp Jackson laccolith and thus be related to the East Mountain stock. If the Viewpoint laccolith is, in fact, a western extension of the Camp Jackson laccolith, it may once have been part of the porphyry mass that extends along the section line between secs. 15 and 22, T. 34 S., R. 22 E. (unsurveyed; pl 1).

SHAY MOUNTAIN STOCK(?) AND RELATED LACCOLITHS

The huge dome known as Shay Mountain is probably underlain by a major igneous body, here tentatively classified as a stock and named the Shay Mountain stock(?). It is the second of the two inferred stocks in the Abajo Mountains—the other being the Johnson Creek stock(?) which probably underlies the Johnson Creek dome (p. 66).

Dikes, sills, laccoliths(?), and bosses, exposed on the crest and along the west, north, and east flanks of Shay Mountain, probably indicate the texture and composition of the buried stock(?).

Shay Mountain is a low, broad dome north of the main mass of the mountains but attached to them on its south flank by a narrow ridge known as Shay Ridge (pl. 2). Most of the dome is in T. 33 S., Rs. 21 and 22 E. (fig. 20). In gross aspect, Shay Mountain is crudely circular, asymmetric (its north flank is steeper), and about 8 miles in diameter. It is composed of strata that range in age from Triassic

(Chinle Formation) to Late Cretaceous (Mancos Shale). These strata dip radially outward from the structural crest of the dome, which is about half a mile north of the topographic center. In general, dips on the north flank average 8° northward, on the east flank about 5° eastward, on the south flank about 11° southward, and on the west flank about 7° westward. These dips decrease away from the dome, until they merge with the regional dip at a distance of about 3 miles.

The top of Shay Mountain is capped by a broad irregular bench of Dakota and Burro Canyon which dips about 6° southward. This cap rock has been deformed into minor folds, and small patches of the Mancos Shale are preserved locally in the downwarped areas. Below this cap rock, the older strata crop out on the flanks of the dome as alternating steep slopes and cliffs. In general, the indurated well-cemented sandstones and those sandstones that are protected by overlying resistant strata stand as cliffs. These include the Wingate Sandstone, parts of the Navajo Sandstone, the Entrada Sandstone, and the lenticular sandstone beds of the Salt Wash Member of the Morrison Formation. Between these cliff formers, the softer mudstone or siltstone beds form steep ledgy slopes. Locally, especially on the east flank of the dome, the Navajo Sandstone is exposed as broad, irregular-surfaced sloping benches separated by deep narrow steep-walled canyons.

Igneous rocks on the east and west flanks are chiefly dark-gray porphyry sills and near-vertical dikes that penetrate Navajo, Carmel, Entrada, Summerville, and Morrison strata. Two large porphyry exposures are on the north flank of the dome. These arch the overlying strata and are tentatively classified as laccoliths. Both are chiefly in Morrison strata. The larger of the two, exposed at the head of Shay Canyon, is called the Shay Canyon laccolith(?); the other, called the North Flank laccolith(?), crops out about half a mile to the east (fig. 20). Both of these laccoliths(?) are now represented by widespread boulder fields through which project small conical masses of severely jointed porphyry. The boulders have moved downslope, and conceal many of the sedimentary contacts.

The highest point on Shay Mountain is a small igneous mass that overlies a remnant of the Dakota and Burro Canyon which dips about 45° northward. This porphyry mass probably is a segment of a former sill, most of which has been removed by erosion.

Dissection of Shay Mountain has not been severe. In general, the adjacent streams have eroded the flanks of the dome, but as yet the dome has not been breached. Consequently, the Johnson Creek and the Shay Mountain domes differ widely in appearance. In the former, most of the strata forming its roof and flanks have been removed. In contrast, Shay dome is still almost whole; only along the north flank do deep canyons reach far back toward the center of the dome.

SHAY CANYON LACCOLITH(?)

Near the head of Shay Canyon, at the intersection of Tps. 32 and 33 S., Rs. 21 and 22 E., a large mass of porphyry, occupying about a fourth of a square mile, is tentatively classified as a partly denuded and eroded laccolith (fig. 20). It is here called the Shay Canyon laccolith(?). The original shape of the laccolith(?) has been destroyed, and it now appears as ridges separated by narrow valleys. As the north flank of Shay Mountain is heavily forested, the contacts between the laccolith(?) and the surrounding strata are concealed. The limits of the laccolith(?) have been determined chiefly on the basis of porphyry float.

In gross aspect the laccolith(?) is estimated to be about 1 mile long and ½ mile wide; it was probably about 400 feet thick when emplaced (pl. 4; table 4). Presumably it was injected about N. 15° E. from the buried tip of the Shay Mountain stock(?).

The laccolith(?), now partly denuded, was once entirely covered by Morrison strata. The east flank of the laccolith(?) is still concealed beneath the Morrison, and in the SW¼ sec. 31, T. 32 S., R. 22 E., a wedge of Morrison overlies the northeast flank. Although exposures are poor, the roof of the laccolith(?) appears to cut across the overlying strata. The laccolithic floor is discordant also, but in general it rests on the basal strata of the Salt Wash Member of the Morrison Formation. Locally it cuts down to and overlies the Entrada Sandstone.

The relation of the Shay Canyon laccolith(?) to the North Flank laccolith(?) is unknown. The two are probably joined beneath the sedimentary strata exposed in the S½ sec. 31, T. 32 S., R. 22 S. (pl. 1).

NORTH FLANK LACCOLITH(?)

An igneous exposure, covering about a tenth of a square mile, follows the west side and crest of a ridge on the north flank of Shay Mountain. This exposure, in the SE¼ sec. 31, T. 32 S., R. 22 E. (fig. 20), is tentatively interpreted as the denuded flank and roof of a laccolith, here called the North Flank laccolith(?). Because of thick cover, it is unknown whether this exposure is, in fact, a laccolith.

The laccolith(?) does not seem to have been severely eroded; the crest, although narrow, is almost straight and the flank is smooth and unbroken. The surface of the laccolith(?), however, has disintegrated to form a huge mass of angular boulders.

Locally these have moved downslope and now conceal many of the underlying contacts.

If it is assumed (a) that the porphyry exposure is the distal part of the laccolithic flank and roof, (b) that the bulk of the laccolith(?) is concealed beneath sedimentary strata, and (c) that the laccolith(?) stems from the buried Shay Mountain stock(?), it can be estimated that the laccolith(?) is about 1½ miles long and ¼ to ½ mile wide and was about 600 feet thick when emplaced (pl. 4; table 4). The direction of emplacement of the laccolith is unknown, but it may have been injected originally about N. 70° E. from the tip of the buried stock(?).

It in unknown which strata were intruded by the laccolith. The very north tip of the porphyry exposure in the center of the E½ sec. 31, T. 32 S., R. 22 E., is interpreted to be the floor of the laccolith. If this assumption is correct, the laccolith, at least in part, rests on the Entrada Sandstone and its flanks are covered by the Summerville and Morrison Formations. Probably the bulk of the laccolith is overlain by Morrison strata.

The North Flank laccolith(?) may be contiguous at depth with the Shay Canyon laccolith(?). The juncture may be concealed beneath the SE¼ sec. 31, T. 32 S., R. 22E.

LACCOLITH NOT RELATED TO A STOCK

Most of the laccoliths in the Abajo Mountains area are related either to a parent stock or to a feeder laccolith. A few, such as the Pole Creek laccolith, and the Corral and Spring Creek laccoliths(?), may be independent of any one stock and may have their own conduits. The field relations of these are such, however, that they may have been formed by magma extruded from the Abajo Peak laccolith. Only one laccolith is known that seems to be completely unrelated to any stock. This laccolith, the Rocky Trail laccolith, is along the south flank of the mountains and is entirely within the Verdure graben (fig. 20).

ROCKY TRAIL LACCOLITH

The Rocky Trail laccolith, in the S½ sec. 26 and the N½ sec. 35, T. 34 S., R. 22 E. (unsurveyed), is about 3 miles south of the East Mountain stock and about 1 mile southwest of the southwest corner of South Peak laccolith.

The laccolith, exposed over an area of about a tenth of a square mile, is estimated to be about ½ mile long and about ⅓ mile wide. Its thickness is unknown, because its floor is not exposed, but I estimate it to have been about 600 feet thick when emplaced (pl. 4; table 4). The Dakota and Burro Canyon overlie the laccolith, and locally have been tilted as much as 22° southward.

The Rocky Trail laccolith is confined entirely within the Verdure graben. Both the north and south flanks of the laccolith abut the faults that bound the graben (p. 45–46). In the center of sec. 35, T. 34 S., R. 22 E. (unsurveyed), a dike, attached at its proximal end to the south flank of the laccolith, extends along the South Vendure fault (pl. 1). A second dike, on the section line between secs. 34 and 35, T. 34 S., R. 22 E. (unsurveyed), also is along and collinear with the South Verdure fault. Neither fault breccia nor gouge was noted along either the dikes or the laccolithic flanks. Here, as elsewhere in the Abajo Mountains, the absence of gouge, and the dikes along the faults, are interpreted to mean that the faults that bound the Verdure graben were formed before the emplacement of the dikes or the Rocky Trail laccolith. Possibly one, or both, of the faults served as channelways for the ascending magma which was injected below the Dakota and Burro Canyon and which arched those units as the laccolith was formed.

SILLS

In the Abajo Mountains area, sills range from very thin concordant tabular sheets to expanded masses of porphyry that resemble laccoliths. Many of these larger sills show minor crosscutting relations with the adjacent sedimentary strata.

The thin sills are as much as 60 feet thick, and some are about half a mile wide. Their extent is unknown, but in a few places where the overlying strata have been stripped, the sills can be traced for as much as 1 mile before they disappear beneath sedimentary rocks. In these localities the exposed upper surfaces of the sills are gently undulatory and marked by small depressions and knobs.

The sills are composed of quartz diorite porphyry similar to that found elsewhere in the mountains. Most of the sills seem to be offshoots of adjacent laccoliths or stocks. In a few places the sills give rise to dikes.

Sedimentary rocks above and below the sills have been baked and altered to form a zone 5 to 8 feet thick in which the rocks have been indurated and their colors lightened.

One well-exposed sill, near the center of the Johnson Creek dome, occupies parts of the S½ sec. 20, and the NE¼ sec. 29, T. 34 S., R. 22 E. (unsurveyed; pl. 1). Part of the sill underlies the Moss Back Member, which in this locality is overlain by the Scrub Oak laccolith (p. 69). Much of the sill is now exposed as a broad hummocky bench. Locally, remnants of the

Moss Back Member are preserved as small buttes whose crests are about 100 feet above the surface formed on the sill. The sill covers about a third of a square mile, and is estimated to be about 1 mile long, ½ mile wide, and about 60 feet thick. Its south edge in the NE¼ sec. 29, T. 34 S., R. 22 E. (unsurveyed), ends along the projected trace of the Dry Wash fault. The absence of both fault gouge and fault breccia along this contact suggests that the fault was established before the sill was emplaced. Apparently, the lateral spread of the magma that formed the sill was halted by, and along, the fault plane.

Other sills are exposed both along the north flank of the Johnson Creek dome and on the flanks of Shay Mountain. An extensive light-gray tabular sill about 15 feet thick is intercalated in the red siltstone beds of the Chinle Formation that form the north flank of the Johnson Creek dome. The sill can be traced for at least 1¼ miles through the SE¼ sec. 18, the NE¼ sec. 19, and the NW¼ sec. 20, all in T. 34 S., R. 22 E. (unsurveyed; pl. 1). The strata bordering the sill have been altered, chiefly in color, to form a zone about 5 feet thick above and below the sill.

Another sill is exposed, about 100 feet above the base of the Entrada Sandstone, on the southeast flank of Shay Mountain in the SE¼ sec. 7, T. 33 S., R. 22 E. (unsurveyed). The sill, which is about 400 feet wide, maintains an almost even thickness of about 35 feet although it thins near its north and south edges. Locally the overlying sandstone has been eroded and the sill forms a dark olive-gray (5*Y* 3/2) cap rock protecting the underlying strata.

Two major igneous bodies, tentatively interpreted as expanded sills, crop out along the upper flanks of Shay Mountain. One, along the north flank, is in the center of the N½ sec. 1, T. 33 S., R. 21 E. (unsurveyed; pl. 1). It is emplaced in the Morrison Formation and appears as prominent knobs projecting through extensive boulder fields. Although exposures are poor, I estimate the sill to be about ½ mile wide and about 250 feet thick. The second expanded sill, possibly best considered as an incipient laccolith, is on the east flank of Shay Mountain along the section line between secs. 6 and 7, T. 33 S., R. 22 E. (unsurveyed). This sill is also emplaced in the Morrison Formation but differs in that its upper surface has arched the overlying strata. It is about one-fourth mile wide and may have been about 600 feet thick when emplaced. The floor of the sill is concealed beneath boulders and dense vegetation.

DIKES

Many of the dikes in the Abajo Mountains area are extensions of igneous bodies formed in the underlying or adjacent sedimentary strata. The dikes appear as small porphyry apophyses collinear with, and obviously controlled by, joints or faults. Generally the dikes are short and are confined to one formation, but one dike on the west flank of Shay Mountain can be traced for about 1½ miles, cutting across all the strata from the Navajo Sandstone to the Brushy Basin Member of the Morrison Formation (pl. 1).

Dikes are common in the main mass of the mountains, but most are poorly exposed because of dense vegetation and thick colluvium. The roofs of buried laccoliths may be marked by small dikes as in the NW¼ sec. 6, T. 34 S., R. 22 E. (unsurveyed), where an elongate dike may represent a protuberance on the distal edge of the Shay Ridge laccolith (p. 64).

Most of the dikes are medium-gray (*N* 5) to dark-gray (*N* 3) quartz diorite porphyry (fig. 14) and contrast markedly with the lighter colored sedimentary rocks. The dikes are nearly vertical and range in length from a few hundred feet to as much as 1½ miles. Commonly they stand as wedge-shaped masses, 20 to 50 feet high and as much as 50 feet wide at the base, that narrow to a knife edge at the crest. Many of the dikes thicken and thin erratically along their length, locally narrowing to as little as 2 feet and elsewhere widening to as much as 300 feet.

Xenoliths of sedimentary rock are common in the dikes, and range from subround fragments as small as one-fourth inch in diameter to boulders whose long axis measures about 12 feet, and whose short axis is about 8 feet. Normally these xenoliths are indurated and somewhat metamorphosed; in consequence they weather as resistant knots and knobs that project above the surface of the igneous material. The margins of the sedimentary rocks adjacent to the dikes are also altered to form a metamorphosed zone about 4 feet wide.

The dikes that intrude the shatter zones around the East and the West Mountain stocks are small and irregularly shaped, and are clearly derived from the stocks. Most of the dikes that cut the strata on Shay Mountain were probably injected from the buried stock (?). These dikes, however, are larger, and their trend and distribution has been determined by established joints and faults.

Many of the dikes exposed elsewhere in the Abajo Mountains area are along major faults, hence the faults were in existence when the dikes were emplaced. Examples of dikes along faults include the two along the South Verdure fault in secs. 34 and 35, T. 34 S., R. 22 E. (unsurveyed; see p. 45–46 and pl. 1). They suggest that the Verdure graben was formed before the dikes were emplaced (p. 46). Another example of a dike along a fault is the prominent dike exposed along the trace to the Mount Linnaeus fault in the center of the NW¼ sec. 19, T. 34 S., R. 22 E. (unsurveyed). Here also the field relations suggest that the fault was in existence when the dike was emplaced (p. 76).

FAULTS

The faults that border the Shay and Verdure grabens extend far beyond the limits of the Abajo Mountains area (fig. 17) and probably were formed before the mountains were domed (p. 46). Because they cut the Mancos Shale of Late Cretaceous age, they must be younger than early Late Cretaceous. In contrast, other faults confined to the mountains were probably formed as the mountains were domed, either in the Late Cretaceous and early Eocene or in the middle Miocene and Pliocene (p. 80). Included in this category are the three faults that partly encircle the Johnson Creek dome: the Dry Wash fault which cuts across Dry Wash and truncates the south edge of the Johnson Creek dome (p. 75), the Mount Linnaeus fault which extends from the south edge of the Dry Wash laccolith across Dry Wash to truncate the west flank of the Johnson Creek dome (p. 76), and the Indian Creek fault whose trend, although uncertain, may have been across the north end of the Johnson Creek dome (pl. 1; p. 76).

These three faults probably were formed during the emplacement of the Johnson Creek stock(?). This stock may well have nearly vertical sides, and can be considered, therefore, to be somewhat like a bysmalith (p. 66–68). As the stock (?) forced its way up, it arched the overlying strata. At some stage, these rocks broke and a plug of sedimentary strata, partly encircled by the faults, was slightly raised. Displacements along the three faults indicate that the greatest movement was near the center of the dome. During the uplift, or shortly after, magma was injected into the overlying and adjacent strata to form dikes, sills, and laccoliths, some of which were intruded along or against these newly established faults.

All the other faults in the area are minor and have small displacements.

DRY WASH FAULT

The west end of the Dry Wash fault is in the center of the W½ sec. 25, T. 34 S., R. 21 E. (unsurveyed), where it abuts the North Verdure fault. From this point, the Dry Wash fault extends eastward 3 to 3¼ miles to the NE¼ sec. 29, T. 34 S., R. 22 E. (unsurveyed; pl. 1). East of Dry Wash the fault trends almost due east as it cuts transversely across the south flank of the Johnson Creek dome In the center of sec. 29, T. 34 S., R. 22 E. (unsurveyed), the fault curves and trends about N. 55° E. Possibly the linearity of the flank of the sill in the NE¼ sec. 29 indicates an eastward extension of the fault (p. 73–74).

For most of its extent, the fault is poorly exposed, although in places it is easily traced where it separates formations having different attitudes. It is best exposed along the valley walls of Dry Wash both in the center of the E½ sec. 25, T. 34 S., R. 21 E. (unsurveyed), and in the center of the W½ sec. 30, T. 34 S., R. 22 E. (unsurveyed; fig. 26). In general, the fault plane is estimated to trend about N 70° E. and to be nearly vertical near its west end, possibly dipping about 80° N. Farther east, along the south flank of the Johnson Creek dome, the fault is normal and its plane dips about 70° S.

The north side of the fault is the upthrown side, and near its west end, Morrison strata (Salt Wash(?) Member) are in contact with similar units south of the fault. Here the throw probably does not exceed 50 feet. To the east in Dry Wash, the Navajo Sandstone, north of the fault, is against the Entrada Sandstone to the south and the displacement is estimated to be about 250 feet. Still farther east along the south flank of the Johnson Creek dome, the Cutler Formation is in contact with the Moab Sandstone Member of the Entrada Sandstone—an apparent throw of almost 1,500 feet. Here, however, this figure may not correctly indicate the displacement, for the beds of the Cutler have been arched and displaced by the Prospect laccolith, which was probably emplaced after the fault was formed (p. 68). Despite this, it is clear that the amount of throw increases to the east. I suggest that the Dry Wash fault began on the east flank of the dome, curved across the

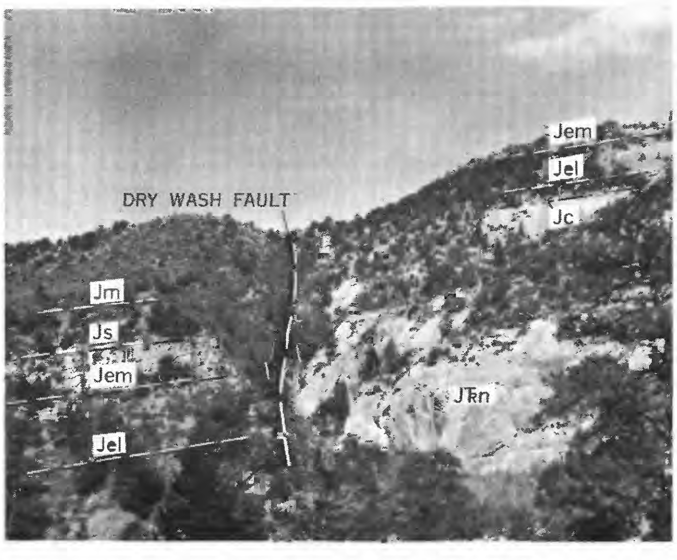


FIGURE 26.—West valley wall of Dry Wash showing the Dry Wash fault, and general relations of stratigraphic units bordering the fault. (J̅R̅n, Navajo Sandstone; Jc, Carmel Formation (middle sandstone); Jel, lower unit of Entrada Sandstone; Jem, Moab Sandstone Member of Entrada Sandstone; Js, Summerville Formation; and Jm, Morrison Formation.)

dome's south edge, and ended against the preexisting North Verdure fault.

MOUNT LINNAEUS FAULT

The Mount Linnaeus fault can be traced for about three-fourths of a mile along a trend of about S. 17° E. from the south tip of a dike in the center of the N½ sec. 19, T. 34 S., R. 22 E. (unsurveyed), to the northwest edge of the exposed Prospect laccolith in the NE¼ sec. 30, T. 34 S., 22 E. (unsurveyed); (pl. 1). The fault truncates the west flank of the Johnson Creek dome in much the same manner as the Dry Wash fault truncates the south flank.

The Mount Linneaeus fault has no topographic expression, and its trace is so completely concealed by vegetation and detritus that it cannot be located precisely. Its trend, however, is shown by the juxtaposition of totally different lithologic units having completely different attitudes. The attitude of the fault plane is uncertain. It may be nearly vertical at its north end and dip 60° to 70° westward along the remainder of its extent.

Although the fault can be traced only for three-fourths of a mile, I believe that it may formerly have been much longer and that parts of it may have been later modified by igneous intrusions. Thus, the north end of the fault is probably followed by the nearly vertical dike in the center of the NW¼ sec. 19, T. 34 S., R. 22 E. (unsurveyed); (see pl. 1 and p. 75). Further, the unusual straightness of the west edge of the Dry Wash laccolith in the center of the S½ sec. 18, T. 34 S., R. 22 E. (unsurveyed), may indicate the former presence of the Mount Linnaeus fault in that area (p. 65). Similarly, the south end of the fault may have determined the linearity of the west edge of the Prospect laccolith (NE¼ sec. 30, T. 34 S., R. 22 E.); (p. 68). The original fault plane, therefore, may be indicated by the linear edges of these two laccoliths.

If the dike and the two laccoliths did, in fact, follow the fault, it may have extended originally 1¾ miles, from the center of the S½ sec. 18 to the NE¼ sec. 30, T. 34 S., R. 22 E. (unsurveyed), where it would have ended against the North Verdure fault.

The beds along the east side of the fault are upthrown, and the displacement increases southward. Near the north end of the fault, lower strata of the Chinle are in contact with the Entrada Sandstone. In contrast, at the south end of the fault, Cutler strata are in contact with sandstone beds tentatively assigned either to the lower unit of the Entrada Sandstone or to the Moab Sandstone Member of the Entrada Sandstone. The displacement is greatest, therefore, where the fault cuts across the southwest flank of the Johnson Creek dome. Clearly the displacement along the Mount Linnaeus fault increases to the south in much the same manner as the displacement along the Dry Wash fault increases to the east. I suggest that the Mount Linnaeus fault began near the southwest edge of the dome and extended northward to end against the West Mountain stock.

INDIAN CREEK FAULT

The Indian Creek fault is poorly exposed beneath dense vegetation and thick detritus. For much of its extent it cuts through Morrison strata and is difficult to trace. The fault is thought to extend for about 1¾ miles from the SE¼ sec. 5, to the center of sec. 17, T. 34 S., R. 22 E. (unsurveyed; pl. 1). In general, it trends about S. 25° W. The fault is nowhere exposed and consequently nothing is known of its attitude.

It seems likely that the trace of the Indian Creek fault has been obscured by intrusive bodies in much the same manner as the Mount Linnaeus fault. In the center of sec. 17, T. 34 S., R. 22 E. (unsurveyed), the south end of the Indian Creek fault can be traced into a narrow elongate dike about 30 feet wide and about 600 feet long (pl. 1). The trend of the dike suggests that it was emplaced along the fault. The dike in turn appears to be an apophysis extending to the north from the northwest tip of the Porcupine laccolith. The west flank of the Porcupine laccolith is unusually straight and follows the projected trend of the Indian Creek fault. There seems to be, therefore, almost a repetition of the relation that exists between the Dry Wash laccolith, its accompanying dike, and the Mount Linnaeus fault.

Further, the unusual stratigraphic relations near the Porcupine laccolith seem best explained by the presence of a fault (fig. 25; p. 70), perhaps an extension to the east of the Indian Creek fault. This fault(?) would have truncated the north flank of the Johnson Creek dome in much the same way as the Dry Wash and Mount Linnaeus faults cut the strata that form the south and west flanks of the dome. The small fault in the SE¼ sec. 16, T. 34 S., R. 22 E. (unsurveyed), may be the eastward extension of this inferred fault (p. 70–71).

I suggest, therefore, that the original Indian Creek fault may have been about 3¼ miles long and that it extended possibly from the SE¼ sec. 5 to the center of sec. 16, T. 34 S., R. 22 E. (unsurveyed). The fault probably began at the northeast flank of the dome, extended northwestward across the north flank of the dome, and was then diverted to the north by the mass of the West Mountain stock.

JOINTS

Except for the joints that are adjacent and parallel to the major regional faults, all other joints in the sedimentary strata can be related to the igneous intrusions. Two types of joints are around each uplift: dip joints, which parallel the dip of the sedimentary strata, and strike joints, which parallel the strike. Wherever exposed, the dip joints are more numerous, better developed, and longer. Commonly the two sets of joints form a nearly conjugate system.

In general, both the dip and strike joints are vertical or nearly so. In detail, however, the joint planes are irregular, curve somewhat, and change attitude. The distance between joints varies; in some places it is only a few feet, elsewhere it is as much as 200 feet. On the surface the joints appear as open cracks, but in the mines they form thin harline cracks that determine the fracture pattern of the rocks. Near the laccoliths and stocks, the joints in the sedimentary strata are filled with silica and commonly stand as narrow ridges 2 to 3 inches wide and 2 to 12 inches high above the adjacent country rock.

Normally the joints cut all the consolidated sedimentary units regardless of differing lithologies and thicknesses; the joints do not deviate where they pass from one unit to another.

Both strike and dip joints are well exposed on Shay Mountain dome. Most of the dip joints radiate outward from the center of the uplift, and most of the strike joints encircle the uplift. Some of the dip joints are only a few feet long, others can be traced for about 2,000 feet; however, most are about 500 feet long. In places, dikes are intruded along the dip joints and appear to have been guided by them (pl. 1). The strike joints curve slightly, but, in general, are concave toward the uplift center. They are shorter than the dip joints and average 300 feet in length, although a few are as much as 1,000 feet long.

Most of the joints are classified as tension joints, and probably developed during the arching of the sedimentary strata as the igneous bodies were emplaced.

The igneous rocks are cut into angular blocks about 2 feet on a side by a roughly conjugate system of joints. The joint planes are irregular and curve but are vertical or nearly so. Most of the joints appear as open gaps about a quarter of an inch wide. These gaps probably serve as channelways for rainwater which, once it enters the gap, freezes and pries blocks loose to form the huge boulder-covered slopes so common in the Abajo Mountain area.

Chiefly because of poor exposures, the broad pattern of the joints in the igneous rocks is not known.

Most of the joints in the igneous rocks are classified as shrinkage cracks; they probably formed during the cooling and contraction of the igneous bodies following their emplacement.

Joints filled with silica and containing sulfide minerals cut the igneous rocks that form the East Mountain stock. The West Mountain stock has also been cut by joints but these are neither as closely spaced nor as widely distributed as those in the East Mountain stock.

The silica-filled joints in the stocks probably were formed after the stock and its encircling laccoliths were emplaced and crystallized. It may be that shortly after the stocks were consolidated they were fractured, possibly by the final movements of the deeply buried crystallizing parent magma. At this time hydrothermal fluids moved up through the newly formed joints, altered the invaded strata, and then deposited sulfide minerals in the host rock and finally silica in the joints.

STAGE OF INTRUSION

As a result of separate studies in the Henry and La Sal Mountains, it has been suggested that the laccolithic centers of the Colorado Plateau are the result of a single intrusive process arrested at each mountain at different stages of development (Hunt, 1946, p. 16; 1953, p. 148; 1954, p. 478). The intruded masses in the separate centers are alike lithologically, form similar structures, invade similar sedimentary strata, and seem to have followed the same sequence of events during emplacement. This similarity suggests that they were emplaced contemporaneously and are derived from the same parent magma. Clearly they could not all have reached the same stage of development at the time they were emplaced.

The intrusive sequence has been divided into three stages, each characterized by igneous rocks of specific composition (Hunt, 1954, p. 478).

Diorite porphyry stage.—The first stage is marked by the injection of large bodies of diorite porphyry, chiefly as stocks and laccoliths. The magma was viscous, had a low temperature (probably about 500° C), contained only small amounts of volatiles (and these seem to have been retained in the injected body), and accomplished little to no alteration of the host rock.

Monzonite porphyry stage.—The second stage is marked by the forceful injection of a body of monzonite porphyry under physical and chemical conditions similar to those that existed during the diorite porphyry stage. During this stage the magma again seems to have been viscous and cool, and to have contained only small amounts of volatiles. The host rocks are but slightly metamorphosed.

Syenite stage.—The third stage is represented in the La Sal Mountains by a "* * * dike swarm of dominantly syenitic dikes, a series of feldspathoidal dikes, and an irregular stock of soda syenite * * *" (Hunt, 1954, p. 478). The first dikes were apparently injected forcibly, but later dikes were emplaced by assimilation of the wall rock. Presumably the magma was at a high temperature, and contained large amounts of volatiles. The escape of these volatiles along joint planes resulted in the deposition of sulfides in the fissures. The final episode in this stage was the formation of explosion breccias, and these may represent the roots of former volcanoes (Hunt, 1954, p. 478).

A fourth stage may be represented in the laccoliths of the La Plata Mountains, where nonporphyritic rocks have stoped and assimilated many of the diorite and monzonite porphyries formed during the earlier stages (Eckel, 1937, p. 260).

The work completed by the Geological Survey on these laccolithic mountains has been designed to test and amplify the concept of an intrusive sequence, as well as to classify each mountain group and determine its place in the proposed order of intrusion. As yet, only the Henry, La Sal, La Plata, Ute, Carrizo, and Abajo Mountains have been studied in detail. In the Henry Mountains two of the three stages are represented, the diorite porphyry and the monzonite porphyry stages (Hunt, 1953, p. 148). All three stages are well represented in the La Sal Mountains (Hunt, 1954). The La Plata Mountains may have a fourth stage in addition to the basic three (Eckel, 1937, p. 260). In the Ute, Carrizo, and the Abajo Mountains only the initial diorite porphyry stage is represented.

The conjectured physical conditions of the parent magma in the Abajo Mountains area resemble those described for the diorite porphyry stage, that is, a magma of high viscosity and low temperature, and containing small amounts of volatiles. The parent magma is thought to have been viscous because fragments of hornblendite are so widely distributed; almost every igneous exposure contains one or more fragments. The temperature is thought to have been low because of the minor alteration of the shale (Mancos) and claystone (Morrison) xenoliths. On the basis of the degree of alteration of coal xenoliths and the degree of induration of shales at the igneous contacts, Hunt (1954, p. 478) estimates temperatures of about 500° C for the magma that formed the diorite porphyry intrusions at middle La Sal Mountain. The magma that formed the Abajo Mountains was probably low in volatiles, inasmuch as deuteric alteration has been slight; all other factors conform to the pattern suggested by Hunt (1954, p. 478) for the diorite porphyry stage in the Henry and La Sal Mountains.

STAGES IN THE EMPLACEMENT OF INTRUSIONS

Each laccolithic center on the Colorado Plateau consists of one or more individual mountain masses. Five can be recognized in the Henry Mountains, three are in the La Sal Mountains, at least two are in the Ute Mountains, only one is recognized in the Carrizo Mountains, and three are in the Abajo Mountains. The three in the Abajo Mountains area are East Mountain, West Mountain, and Shay Mountain. Each appears as a distinct topographic prominence joined to the others by low ridges and divides (pl. 2). The well-dissected Johnson Creek dome may represent a fourth such mass, but one so eroded that it is overshadowed by the larger, more prominent adjacent masses of East and West Mountain.

Most of the mountain masses in the laccolithic centers consist of a central stock surrounded by a shatter zone, through which protrude the satellite laccoliths (p. 46). This relation of stocks to shatter zones and laccoliths was first recognized in the Henry Mountains. It was soon realized that the various mountain masses in the Henry Mountains had reached different stages of emplacement as a result of one process operating under similar conditions (Hunt, 1953, p. 148).

As yet, a complete classification has not been established for the stages of emplacement undergone by all the mountain masses in the laccolithic centers. The original five stages proposed (Hunt, 1953, p. 148) range from a simple dome of moderate uplift, underlain by an inferred small stock (Navajo Mountain), to a huge complex dome of considerable uplift that contains a large stock encircled by a shatter zone, huge linear laccoliths, and bysmaliths (Mount Ellen in the Henry Mountains).

As a result of the study of the Abajo Mountains area, one additional stage of emplacement can be added to the five originally proposed. For purposes of clarity and completeness, the proposed expanded classification is given below.

1. The first stage is the simple dome, presumably underlain by a stock. Igneous rocks are not exposed. A typical example is Navajo Mountain in southern Utah.
2. The second stage represents a slight advance over the first stage. It is a simple dome underlain by a small stock from which very small laccoliths, sills, and dikes radiate in all directions. The volume of intruded igneous rock is believed to exceed that of the first stage. This second stage is represented by Mount Holmes in the Henry

Mountains (Hunt, 1953, p. 148) and by Shay Mountain and the Johnson Creek dome in the Abajo Mountains.

3. The third stage is still farther advanced. Doming, reflecting the volume of intruded igneous rock, exceeds that of the previous stages. The center of the dome contains a moderate-sized stock which is ringed by a shatter zone and by laccoliths, sills, and dikes (Hunt, 1953, p. 148). This stage is exemplified by Mount Ellsworth of the Henry Mountains.
4. The fourth stage is marked by steeper doming than the previous stages and reflects a greater volume of intruded igneous rock. At the center of the dome is a large stock encircled by a shatter zone through which protrude tonguelike laccoliths, sills, and dikes. Bysmaliths are also formed. This stage is represented by Mount Hillers and Mount Pennell of the Henry Mountains (Hunt, 1953, p. 148), and by West Mountain of the Abajo Mountains. This stage of emplacement has probably been reached by most of the mountain masses in the laccolithic centers.
5. The fifth stage, newly recognized and, so far, only in the Abajo Mountains area, consists of doming and a volume of intruded igneous rock which exceed that of the previously known stages. In addition to a large stock encircled by a shatter zone, this stage is characterized by several large feeder laccoliths, each partly surrounded by smaller fringe laccoliths. Sills and dikes are common. East Mountain in the Abajo Mountains exemplifies this stage.
6. The sixth and final stage of this expanded classification is marked by extreme doming and large volumes of intruded igneous rock. A large stock, at the center of the dome, is encircled by a shatter zone. Huge linear tonguelike laccoliths are attached to, and radiate in all directions from, the stock; in addition, bysmaliths have been formed. Sills and dikes are common. This stage is the most advanced stage so far recognized. Mount Ellen of the Henry Mountains is an example of this stage.

The expanded classification proposed is by no means a final statement. As other laccolithic centers are mapped, new stages will undoubtedly be found until a complete sequence exists from the simplest to the most complex.

VOLUME OF STOCKS AND LACCOLITHS

Data pertaining to the laccoliths of the Abajo Mountains area are shown in table 4. The total volume of intruded rock, including both stocks and laccoliths, is about 5.2 cubic miles. Of this amount, the laccoliths account for 4.8 cubic miles and the four stocks account for 0.4 cubic miles. The volume of the stocks has been computed on the assumption that each of the two known stocks has straight sides, and each extends at least to a depth equal to the structural relief of the mountains. The two inferred stocks are assumed to have volumes comparable to the exposed stocks.

The figure of 5.2 cubic miles compares with 12.0 cubic miles of intruded rock in the La Sal Mountains (Hunt, 1958, p. 347) and 16.35 cubic miles of intruded rock in the Henry Mountains (Hunt, 1953, p. 144). Comparable volumetric data are not available for the Ute or Carrizo Mountains.

AGE OF INTRUSIONS

The age of the intrusions in the Abajo Mountains area is unknown. The youngest formation intruded by igneous rocks is the Mancos Shale of Late Cretaceous age. The mountains, therefore, are not older than Late Cretaceous. How much younger they are is uncertain. Lead-alpha determinations of zircon concentrates from igneous rocks collected in the Abajo Mountains area have yielded anomalous results (T. W. Stern, written communication, 1958). This uncertainty regarding the age of the intrusions in the Abajo Mountains applies to the other laccolithic centers as well.

A basic assumption made by geologists who have studied the laccolithic centers on the Colorado Plateau is that they were all emplaced almost contemporaneously. Hayden (1877, sheet 17) implied contemporaneity by showing the La Sal, Abajo, Ute (El Late), Carrizo and La Plata Mountains as similarly colored units on his cross sections. Cross (1894, p. 216), referring to the Abajo Mountains, stated, "It can be said that the intrusions were doubtless nearly contemporaneous with those of the Henry Mountains, at about the same geological horizon, and presumably under similar conditions in other respects." Hunt (1956, p. 42) implied contemporaneity by stating, "The igneous centers on the Colorado Plateau are regarded as Miocene, or younger * * *." Shoemaker (1956, p. 162) stated, "* * * it seems reasonable to assume that most of the laccolithic clusters of the central Plateau were intruded almost contemporaneously." This concept of contemporaneous emplacement is based chiefly on the similarities of the laccolithic centers: all have similar rock types and structures, all are in similar sedimentary strata, and all have been emplaced in much the same manner. If this concept of near-synchronous emplacement is valid, then obviously the age of any one of the centers is the age of all.

Of the laccolithic centers, the La Plata and Rico Mountains, along the southwest flank of the San Juan Mountains, seem to offer the most reasonable hope for age determination by field methods. The relations of these igneous centers to the adjacent sedimentary strata and to the peneplain surfaces are such that conjectures can be made as to their age.

Igneous activity in the San Juan Mountains can be related to two specific episodes in geologic time (Larsen and Cross, 1956, p. 220). The first occurred during Late Cretaceous and early Paleocene time; the second began during the middle Miocene and may have continued through early Pliocene. No igneous activity can be related to the intervening Eocene, Oligocene, and early Miocene intervals. It would seem, therefore, that the La Plata and Rico Mountains must have been formed during one of these two episodes, either the Late Cretaceous and early Paleocene or the middle Miocene and Pliocene.

A Late Cretaceous age for the La Plata Mountains has been suggested by Shoemaker (1956, p. 162). He noted the presence of igneous debris in the McDermott Member of the Animas Formation (Late Cretaceous age), and suggested that the debris had been derived from dissection of the La Plata Mountains. He stated,

> As the McDermott member is traced northward in the San Juan Basin, the amount of igneous material in it increases, and the fragments of detritus reach a maximum size directly opposite the La Plata Mountains, which lie 12 miles distant from the nearest McDermott strata. Boulders of porphyry from the McDermott, some as much as 3 and 4 feet across, are lithologically similar to the diorite porphyry of the La Plata Mountains. Preliminary study of the trace-element composition indicates that the composition of boulders in the McDermott is like that of the laccolithic rocks of the central Colorado Plateau (including the La Plata Mountains) and is significantly different from the igneous rocks of the San Juan Mountains. The conclusion seems justified that at least some of the coarse debris in the McDermott member of the Animas formation was probably derived from the La Plata igneous center and that some of the intruded masses of the La Plata Mountains are probably of latest Cretaceous age.

Laccoliths and sills of Late Cretaceous or early Eocene age are in the San Juan Mountains near Ouray, Colo. (Burbank, 1930, p. 201; 1936, p. 236), but these are considered to be older than the intrusive masses which formed the La Plata and Rico Mountains (Larsen and Cross, 1956). Eckel (1949, p. 42), however, although uncertain as to the age of the igneous rocks in the La Plata Mountains, stated,

> The similarity in form and composition of the rocks in both the La Plata and Rico domes with the Late Cretaceous or early Tertiary rocks at Ouray strongly suggests that all three groups are of the same age.

Much of the evidence for the Miocene age of the La Plata and Rico Mountains is based on the relation of these mountains to the San Juan peneplain. This extensive peneplain was named and described by Atwood and Mather in their physiographic study of the San Juan Mountains; its age they considered to be late Pliocene (1932, p. 25) because it truncates strata of both the "Fisher and Potosi epochs" (Miocene) and is overlain by the volcanic rocks of the Hinsdale Formation (Pliocene(?)).

Both the La Plata and Rico Mountains are believed to have formed after deposition of the Wasatch Formation of Eocene age and before the development of the San Juan peneplain of late Pliocene age (Larsen and Cross, 1956, p. 220). Thus, many of the broad surfaces that truncate the La Plata and Rico Mountains are related to the San Juan peneplain; further, components of the gravel remnants that cover the peneplain near the La Plata Mountains have been correlated with the intrusive bodies in the mountains (Atwood and Mather, 1932, p. 66, 67).

This relation suggests that the intrusions in the La Plata and Rico Mountains were emplaced during the Miocene—the second period of igneous activity noted in the San Juan Mountains. On the basis of this reasoning, the laccolithic mountain groups on the Colorado Plateau (including the Abajos) could be considered to be Miocene in age.

The mid-Tertiary age assigned to the La Plata and Rico Mountains by Larsen and Cross (1956), however, depends on the former existence of the San Juan peneplain. Whether such a peneplain did, in fact, exist is now in doubt as a result of 1958–59 work in the central and eastern San Juan Mountains by T. A. Steven of the U.S. Geological Survey. Steven (written communication, 1959) noted,

> My work * * * has caused me to be very suspicious that any such peneplain ever existed. In the Summitville area, the remnants of this surface chosen by Atwood and Mather can be shown to have had diverse origins, and none appear to me to have been part of any widespread surface of low relief such as required by the peneplain concept * * *.
>
> A similar situation exists in the Creede area where the chosen remnants of the so-called San Juan peneplain are only a few of many high-level areas of low relief, and many of these can be shown to have had diverse origins. Even more telling against the peneplain concept, however, is the history of the Rio Grande Valley. This history is at present only partly understood, but so far as can be told, a canyon several thousand feet deep below the level of the so-called San Juan peneplain existed all through the time when the peneplain was supposed to have been forming * * *.

Hunt (1956, p 42, 45, 82) also suggested that the laccolithic mountain centers on the Colorado Plateau were emplaced in late Miocene or early Pliocene.

In support of this age assignment, he offered three main lines of evidence. First, he noted the petrographic similarity among the laccolithic clusters, the volcanic centers along the southwest edge of the Colorado Plateau, and the Mount Taylor and San Francisco volcanic fields. He suggested that, inasmuch as the volcanic areas are dated as "* * * mid-Tertiary, perhaps Miocene * * *," the same age may apply to the laccolithic clusters (Hunt, 1953, p. 212). Second, he suggested that the Henry and La Sal Mountains antedate the deep canyon cutting, because debris shed by these mountains is found on the rims of the canyons near the mountains (Hunt, 1956, p. 45). The deep canyon cutting is dated as Pliocene and possibly Miocene (Hunt, 1953, p. 212). Consequently, the mountains are considered to be late Miocene or early Pliocene (Hunt, 1956, p. 45). The third line of evidence suggested by Hunt (1956, p. 43, 45) is based on the apparent diversion of streams by the laccolithic centers (fig. 27). The fact that many of the major streams on the Colorado Plateau cut across the orogenic structures but seem to bend around the laccolithic centers suggests that these centers are younger than the orogenic structures. As examples, two streams can be cited whose courses are indifferent to the orogenic structures, namely, the San Juan River that cuts across the Monument upwarp west of Bluff, Utah, and Muddy Creek, a tributary of the Dirty Devil River, which transects the south end of the San Rafael swell. Examples also can be cited of some major streams that seem to have been diverted by the laccolithic centers. The San Juan River apparently has been influenced by the location of the Ute and Carrizo Mountains, for it flows between them in a broad synclinal valley. The Fremont River (another tributary of the Dirty Devil River) swings in a wide arc around the north end of the Henry Mountains, and the Dolores River swings to the north around the north flank of the La Sal Mountains. This indifference to the orogenic structure and apparent diversion by the laccolithic centers suggest to Hunt (1953, p. 212) that the stream courses were probably determined in the Tertiary. He stated,

> This adjustment would have developed if doming of the laccolithic mountains dammed earlier stream courses, forcing streams like the Fremont and Dolores into new courses. Inasmuch as both streams now follow the structurally lowest course possible they may have been flowing across Tertiary basin sediments when the intrusions occurred, and their courses shifted monoclinally off the domed areas even though the doming progressed slowly.

The preceding discussion shows that the age of the laccolithic mountain groups on the Colorado Plateau is still uncertain. The similarity between the igneous detritus in the McDermott Member and the igneous rocks of the La Plata Mountains and the increase in size of the detritus as the mountains are approached (p. 80) strongly suggest that the La Plata Mountains were being eroded during the formation of the McDermott Member (Upper Cretaceous). Further support for this Late Cretaceous or early Paleocene age for the La Plata and Rico Mountains is the similarity noted by Eckel (1949, p. 42) between the igneous rocks in the La Plata and Rico Mountains and those laccoliths of known Late Cretaceous or early Eocene age near Ouray, Colo. (Burbank, 1930, p. 201; 1936, p. 236). Hence, although evidence is vague, inconclusive, and contradictory in places, nevertheless it seems likely that the age of the laccolithic mountains on the Colorado Plateau is Late Cretaceous to early Eocene. Because it is assumed that the laccolithic clusters were all formed contemporaneously, the age of the intrusive bodies in the Abajo Mountains area is assigned to the Late Cretaceous or early Eocene.[3]

GEOLOGIC HISTORY

Cambrian, Devonian, Mississippian, and Pennsylvanian strata probably underlie the Abajo Mountains area, but as of 1963 none of the test wells drilled in the mapped area have reached them. These strata, penetrated, however, by wells drilled near the Abajo Mountains, are chiefly limestones and dolomites, and represent marine deposits in seas that spread eastward from the deeper basins that lay westward in Utah, Nevada, and Idaho.

By the beginning of Permian time, the area now occupied by the Abajo Mountains probably appeared as a low featureless plain sloping gently westward. Far to the east, westward-flowing streams began to dissect the Uncompahgre highland and to spread the detritus across the plain in broad sheets. Near the mountains the material was coarse; away from the mountains finer grained sediments were deposited. These finer grained sedimentary rocks can now be divided into two units of red beds (the Halgaito Tongue below, and Organ Rock Tongue above) intercalated with two eolian sandstones (the Cedar Mesa Sandstone Member below, and De Chelly Sandstone Member above). These four units are grouped together as the Cutler Formation and represent two separate epi-

[3] Since this report was prepared, detailed geologic mapping by D. L. Gaskell and L. H. Godwin (oral communication, 1963) in the West Elk Mountains of western Colorado has indicated that these mountains are a laccolithic complex similar in many respects to those on the Colorado Plateau. In the West Elk complex, the intrusions invade and displace strata of the Wasatch Formation, a unit generally assigned to the Eocene. These relations suggest that the West Elk laccolithic complex, and by inference, the other laccolithic complexes on the Colorado Plateau, were formed at some time post-Eocene, presumably during the Miocene and Pliocene.

sodes of stream deposition interrupted by two periods of aridity. Only the Cedar Mesa Sandstone Member and Organ Rock Tongue are believed to be in the Abajo Mountains area, and of these only the Organ Rock Tongue is exposed.

During much of the Triassic and Jurassic, the area now occupied by the Abajo Mountains was repeatedly submerged beneath shallow marine seas. Each time the seas withdrew, arid conditions prevailed during which dry winds spread quartzose sand far and wide. A major break in this monotonous repetition of either marine submergence or extreme aridity came about with the gradual elevation of an ancestral highland in the area now known as the Causeway.

At the beginning of Triassic time, the area appeared as an undulatory plain that sloped westward. During

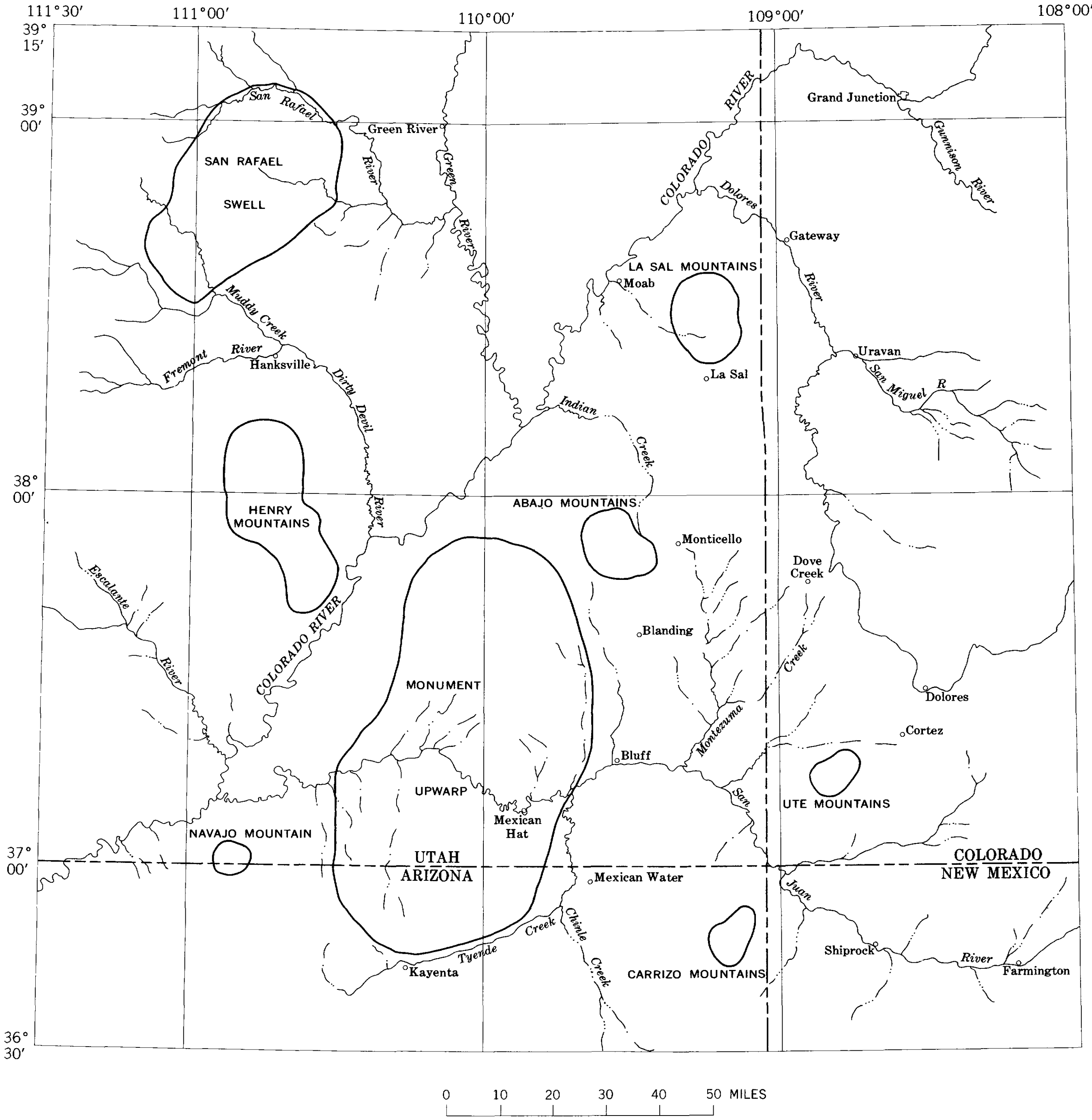


FIGURE 27.—Relations of the laccolithic centers to some of the major streams in the central Colorado Plateau.

Early and Middle(?) Triassic an extensive sea encroached upon this plain from the west, and most of the sediments that now form the Moenkopi Formation in the Abajo Mountains area were deposited in the shallow waters along the east shoreline of this sea. The source sediments were probably brought in by westward-flowing streams originating in the highlands of western Colorado (Baker, 1933, p. 36).

Upon the withdrawal of the Moenkopi sea, streams flowing northward from a newly raised highland in central Arizona spread coarse clastics across the exposed surface (McKee, 1951, p. 493–494); these clastics now form the Shinarump Member of the Chinle. The very north limit of deposition, as suggested by the thin lenticular nature of the Shinarump, was probably near the Abajo Mountains area. As the turbulence of the streams gradually diminished, a period of quiet deposition began during which streams of low gradient deposited in broad coalescing fans the fine-grained sediments that form the rocks now grouped as the lower unnamed member of the Chinle. Rejuvenation of the northward-flowing streams resulted in the deposition of coarse clastics once again; these constitute the Moss Back Member of the Chinle. Again, this deposition was followed by a period when slow, gently flowing streams deposited fine-grained sediments that now form the basal part of the upper unnamed member of the Chinle. Near the end of this episode, arid conditions were imposed on the area; playa lakes were formed in which sandy limestones were deposited. In time the area was covered with transitional deposits—part eolian, part fluvial—that form the upper part of the upper unnamed member of the Chinle. Finally, extremely arid conditions predominated and the area was covered with sand dunes now represented by the Wingate Sandstone of Late Triassic age.

As the desertlike conditions moderated, the streams that had been confined to the edges of the desert gradually extended their courses, and in time covered the area with fluvial deposits (Baker, Dane, and Reeside, 1936, p. 53). These deposits are mapped as the Kayenta Formation of Late Triassic(?) age. This episode of fluvial deposition was brought to a halt by renewed aridity. Once again the area became a desert, and a new accumulation of wind-worked sand was deposited to form the Navajo Sandstone of Triassic(?) and Jurassic age.

The arid conditions that prevailed during Navajo time were halted by the advance from the northwest of an extensive marine sea, known as the Carmel sea (Baker, Dane, and Reeside, 1936, p. 54), which truncated and beveled the Navajo Sandstone and deposited the reworked material on the even surface cut across the Navajo. Upon consolidation, these basal sediments formed the reworked zone of the Carmel Formation of Middle and Late Jurassic age.

The distribution of the several units tentatively assigned to the Carmel suggests that, shortly after the Carmel sea advanced across the mapped areas, an ancestral highland began to rise near the locality now occupied by the Causeway. Thus, the absence from this general locality of strata (lower red) deposited during this phase of the advance of the Carmel sea, implies that the rapid elevation of the ancestral highland restricted the waters of the Carmel sea. Shortly after the rise of the ancestral highland, arid conditions returned temporarily to the Abajo Mountains area; dune sand was deposited rapidly enough to bury the slowly rising highland, and these deposits (middle sandstone) extend across the Abajo Mountains area. A readvance of the Carmel sea ended this arid period, but again the ancestral highland rose rapidly enough to prevent the waters from inundating the entire area. Deposits of this readvance have been called the "upper red," and they also are missing from the general locality near the Causeway. This readvance of the Carmel sea was followed by a major withdrawal. Once again the entire area became a desert and was buried beneath huge deposits of dune sand, which are now mapped as the Entrada Sandstone of Late Jurassic age.

A major readvance of the Carmel sea over much of this part of the central Colorado Plateau brought this arid period to a close. The Abajo Mountains area, however, remained above water, possibly because of the ancestral highland. Although none of the products of this advance were deposited in the mapped area, they were deposited to the south where they have been correlated with the basal part of the Summerville Formation. Shortly after these sediments were deposited, there was a new onset of aridity, and much of the region was again concealed by dune sand, now mapped as the Moab Sandstone Member of the Entrada Sandstone. This arid episode was brought to a complete halt by still another widespread advance of the sea. This time the entire region was inundated, and the deposits of this advance, which cover the entire Abajo Mountains area, have been mapped as the Summerville Formation. Southward, beyond the pinchout of the Moab Sandstone Member, these deposits cannot be differentiated from similar rocks that form the basal part of the Summerville.

Probably the gradual elevation of the ancestral highland ended or slowed either before or during this last advance of the sea, for all sedimentary units deposited subsequently extend unbroken across the Abajo Mountains area.

Near the close of Summerville time, a large highland rose midway along the State line between Arizona and Utah (Craig and others, 1955, p. 135). Northeastward-flowing streams, heading in this highland, spread detritus across the central Colorado Plateau in the form of broad coalescing alluvial fans that now constitute the Morrison Formation. Initially these streams had a high gradient, and they transported and deposited the coarse sediments that make up the Salt Wash Member of the Morrison. As the stream gradients moderated, finer grained sediments were deposited; these now form the Brushy Basin Member of the Morrison.

By the close of Morrison time, the entire Abajo Mountains area was concealed beneath fine-grained continental deposits. The area was part of a broad plain that sloped gently eastward from a slowly rising highland in western Utah. Streams, debouching from this highland, spread coarse clastics over the plain. As these streams shifted back and forth, they gradually reworked the previously deposited sediments, cut new channels, and refilled old ones. Locally swampy areas were formed when stream courses shifted, and there trees grew, flourished, and died. Each of these marshes gradually accumulated a thick deposit of decaying vegetation. In time, as a result of the continuous shifting of the streams, many of the marshes were buried, but even as one was being buried, others were formed. The coarse clastics that contain local lenses of low-grade coal (derived from the vegetation accumulated in the marshes) have been mapped as the Dakota and Burro Canyon.

The eastward-flowing streams emptied eventually into an extensive sea, known as the Mancos sea, which was slowly moving northward and covering the former land surface. In time, the Abajo Mountains area was submerged beneath this sea, and the fine-grained black sediments, now mapped as Mancos Shale, were deposited.

If the laccolithic centers were emplaced during the Late Cretaceous, this was a time marked by rapid and significant events in the Abajo Mountains area. Probably the first major event was the formation of the Shay and Verdure grabens, two of many similar grabens exposed both west and east of the Abajos Mountains (fig. 17). It seems likely that the grabens were formed synchronously by regional forces, whose origins are as yet unknown. The igneous activity that formed the Abajo Mountains may have begun shortly after the grabens were formed and was possibly related to the regional forces responsible for the grabens.

The stocks were probably emplaced almost contemporaneously, possibly as magmatic surges that overlapped one another in time. As one stock was emplaced and began extruding magma to form laccoliths, another stock was probably forcing its way upward, arching and disrupting the overlying strata.

I suggest that the West Mountain stock was the first to be emplaced. At least five laccoliths were formed by magma extruded from this stock.

Probably the next stock to form was the Johnson Creek stock(?). It did not rise as high as the West Mountain stock, but as it arched the beds to form the Johnson Creek dome, it broke the overlying strata and formed the Dry Wash, Mount Linnaeus, and Indian Creek faults. The northward deflection of the Indian Creek fault suggests that the West Mountain stock was either in existence or forming when the beds were faulted. Further, the relation of the Dry Wash laccolith and the dike in the center of the N½ sec. 19, R. 34 S., R. 22 E. (unsurveyed), to the Mount Linnaeus fault suggests that both the West Mountain stock and the Johnson Creek stock(?) were active at about the same time. Five(?) laccoliths were formed in the folded strata of the Johnson Creek dome by magma extruded from the Johnson Creek stock(?).

The East Mountain stock was probably the third to be emplaced. Many of its laccoliths overlie the toes of those laccoliths related to the West Mountain stock and the Johnson Creek stock(?). Fifteen laccoliths can be related to the East Mountain stock.

Probably the Shay Mountain stock(?) was also emplaced during this time. Magma derived from this stock(?) formed two bodies, tentatively interpreted as laccoliths.

The closely spaced quartz-filled fractures in the East and the West Mountain stocks were probably formed shortly after the stocks and laccoliths were emplaced and consolidated. The East Mountain stock was among the last of the stocks to be emplaced, and the final minor readjustments of the deeply buried parent magma affected this stock more than the others. The residual fluids concentrated during this final crystallization were squeezed into and through the fractures. When the temperature and pressure subsequently decreased, these solutions precipitated sulfides, and finally cemented the fractures with quartz. The East Mountain stock was probably the last stock to be emplaced, and it, therefore, carried the largest volume of these fluids; consequently, most of the sulfides were deposited in and near that stock.

It is doubtful whether the solutions responsible for the uranium-vanadium deposits were included with these residual fluids. The complete absence of uranium-vanadium deposits in, and adjacent to, the stocks implies such a lack. Further, one of the uraniferous ore bodies on Shay Mountain is cut by a fault parallel to the strike joints which encircle Shay Mountain (p. 91). Inasmuch as these fractures were formed during the doming of Shay Mountain, the fact that one of them cuts and offsets an ore body suggests that the ore body existed before the mountains were domed—that is, before the intrusions were emplaced.

As the Abajo Mountains were forming, consequent streams began to strip the sedimentary cover. In time, many of the laccoliths were denuded, and igneous debris was spread far and wide to form flanking pediment deposits. Porphyry fragments, derived from the dissection of the Abajo Mountains, are in the alluvium of most streams north, east, and south of the mountains. The fragments have not been spread to the west, however, chiefly because Elk Ridge was either in existence before, or was formed synchronously with, the doming of the Abajo Mountains.

Locally, the faults that flank the grabens have guided drainage and faultline scarps have been formed. For the most part, however, the consequent drainage lines established when the mountains were domed cross the grabens unmodified.

MINERAL RESOURCES

Deposits of economic interest include uranium and vanadium, possible oil and gas, gold and silver, copper, water, sand and gravel, and boulders of igneous rock for possible use as riprap.

URANIUM-VANADIUM DEPOSITS

The first concerted search for uranium-vanadium deposits in the Abajo Mountains area was made in 1944 and 1945 by geologists of the Union Mines Development Corp. (p. 6). As a result of their work, the areas underlain by the major host rock—the Morrison Formation—were delineated, and several small mineralized deposits were found.

In 1948, the U.S. Atomic Energy Commission established a buying policy for uranium-vanadium ore that resulted in intensive prospecting in and adjacent to the Abajo Mountains. Many of the prospectors reached the conclusion that there was a radial distribution of the uranium-vanadium deposits around the laccolithic centers. E. V. Reinhardt (written communication, 1952) stated, "* * * all the major deposits in the Morrison Formation are grouped around the various igneous masses which are scattered irregularly throughout the Colorado Plateau."

The general interpretation was that the mineralizing solutions came from the laccolithic mountains and that the uranium-vanadium deposits were concentrated in the surrounding sedimentary rocks. By 1954, most of the Abajo Mountains area underlain by sedimentary rocks had been staked as mineralized claims. Wooden 4 by 4's used as claim corners became part of the landscape. Certainly all the exposures of the Morrison Formation and the Moss Back Member of the Chinle were claimed.

Despite the active staking of claims, it is uncertain how thoroughly these units have been investigated. Locally, where the exposures are easily accessible, prospecting has been intensive and has been repeated periodically. Where the exposures are remote, however, the prospecting has been chiefly reconnaissance. In general, the results have been disappointing; only seven mineralized centers have been found, and of these only three have produced uranium-vanadium ore. Possibly other deposits are concealed beneath vegetation and detritus.

It should be stressed that the general remoteness and inaccessibility of the area and the dense vegetation and thick colluvial deposits make prospecting difficult, time consuming, and extremely expensive. Many of the prospectors who visited the area searched the stream beds for indicative fragments of float. Others walked along the outcrops of possible ore-bearing beds. Whatever the technique, the poor exposures coupled with the arduous nature of the work have restricted any one man's search to a relatively small area. Most of the prospectors were soon convinced that their time and money would be better spent in areas away from the mountains where the formations were better exposed. As a consequence, prospecting gradually decreased from 1955 to 1957, and by the fall of 1957 most of the prospectors had moved away from the Abajo Mountains area.

Among the sedimentary units exposed in the area, only four are considered possible host rocks for uranium-vanadium deposits—the Shinarump Member of the Chinle Formation, the Moss Back Member of the Chinle Formation, the Entrada Sandstone, and the Salt Wash Member of the Morrison Formation. Of these, the Shinarump Member and the Salt Wash Member seem to offer the best possibilities. The Shinarump Member contains rich uraniferous deposits elsewhere on the Colorado Plateau; however, in the Abajo Mountains area, it is thin, lenticular, and exposed only in a very small area near the center of the dissected Johnson Creek dome. Uranium minerals were not seen during the examination of the Shinarump exposures, and unusual radioactivity was not noted. But where the Shinarump Member is thicker—and unfortunately, in the Abajo Mountains, such thicker sections are probably deeply buried beneath younger strata—it may contain rich uraniferous deposits. The Salt Wash is considered to be favorable, for its exposures in the mapped area do contain uranium-vanadium deposits. The Moss Back Member is barren in the Abajo Mountains area, but directly west of the mountains, a small uraniferous deposit is in sedimentary rocks of the Moss Back and its presence implies that the unit may contain ore in the mapped area. The Entrada Sandstone also is thought to be barren, but it is included here chiefly because in one locality slight radioactivity was noted.

SHINARUMP MEMBER OF THE CHINLE FORMATION

All the exposures in the Abajo Mountains area tentatively correlated with the Shinarump Member of the Chinle Formation crop out in the SE¼ sec. 19 and in the SW¼ sec. 20, T. 34 S., R. 22 E. (unsurveyed). These exposures appear as thin lenses of yellowish-gray (5*Y* 8/1) to light greenish-gray (5*GY* 8/1) massive crossbedded medium- to course-grained sandstone (p. 13). Similar sandstone lenses have been mapped in the Elk Ridge area as part of the lower strata of the Chinle (R. Q. Lewis, Sr., oral communication, 1956), and they contain most of the uranium-vanadium ore deposits in that area.

In the Abajo Mountains area the few exposed Shinarump lenses are barren; no appreciable radioactivity was noted and uranium minerals were not found. Nevertheless, it seems likely that other concealed Shinarump lenses in the area might be favorable host rocks for uranium-vanadium deposits, in view of the uraniferous content of the sandstone lenses in the Elk Ridge area. The search for them would be difficult, principally because of their lenticular nature, but it could be rewarding.

MOSS BACK MEMBER OF THE CHINLE FORMATION

The Moss Back Member of the Chinle Formation crops out in two localities. It is most widely exposed as several benches that flank North Cottonwood Creek in the center of T. 32 S., R. 21 E. It is also exposed as isolated remnants in the center of the Johnson Creek dome in secs. 19, 20, and 29, T. 34 S., R. 22 E. (unsurveyed).

In the Abajo Mountains area, the Moss Back is a resistant sandstone unit that commonly stands as a nearly vertical cliff 50 to 100 feet high. In most places it is a light-gray (*N* 7) to yellowish-gray (5*Y* 7/2) massive crossbedded well-cemented fine- to coarse-grained sandstone that has intercalated lenses of conglomerate and conglomeratic sandstone near its base (p. 14). The Moss Back along North Cottonwood Creek can be traced into the Elk Ridge area where it contains several small uranium-vanadium deposits. These are in strata that fill an ill-defined channel (R. Q. Lewis, Sr., oral communication, 1957), known as the Horseshoe channel, in the SE¼ sec. 7, and the SW¼ sec. 8, T. 33 S., R. 21 E., about 1 mile west of the west boundary of the Abajo Mountains area. The channel trends about N. 55° E., and a projection of the channel would bring it into the Abajo Mountains area in the SW¼ sec. 4, T. 33 S., R. 21 E. (unsurveyed). However, if the channel does persist into this locality, it is buried beneath a thick layer of upper strata of the Chinle.

In the Abajo Mountains area, chiefly along the east valley wall of North Cottonwood Creek (secs. 27 and 28, T. 32 S., R. 21 E.), small areas of the Moss Back Member have been explored by drilling programs underwritten by private concerns. Neither radioactivity nor uranium minerals were found.

Remnants of the Moss Back Member of the Chinle near the center of the Johnson Creek dome are ringed with float, which effectively masks the lower contact. In those few places where the contact is exposed, neither radioactivity nor uranium minerals were noted.

Although the Moss Back Member is more extensively exposed in the Abajo Mountains area than the Shinarump and presents fewer problems for exploration, it is not likely to contain ore deposits as the underlying Shinarump. In the Elk Ridge area where the Moss Back is widely exposed and has been thoroughly examined, only the few ore deposits in the Horseshoe channel have been found. By contrast, the underlying Shinarump contains as many as 15 ore deposits. It would seem reasonable to infer, therefore, that, although the Moss Back may contain ore deposits, they are likely to be small, widely separated, and confined to channel fill.

ENTRADA SANDSTONE

The Entrada Sandstone is included here as a possible host rock for uranium-vanadium deposits chiefly because small amounts of radioactivity have been noted at one locality. The radioactivity is associated with exposures of copper minerals in the abandoned Tuffy Copper mine (SW¼ sec. 5, T. 33 S., R. 22 E., unsurveyed; p. 104) on the east flank of Shay Mountain. The mine is about 30 feet above the base of the Entrada Sandstone. Details of the mine and pertinent geologic features are shown in figure 38. No uranium minerals were found, and I doubt whether any sizable uraniferous deposits are in the Entrada Sandstone of the Abajo Mountains area.

In this area, the Entrada Sandstone is very pale orange (10*YR* 8/2), massive, crossbedded, friable, and very fine to medium grained.

In the Tuffy Copper mine, most of the copper minerals and associated radioactivity are related to joints, and crossbedding planes in the Entrada Sandstone.

Most of the joints in the mine trend between N. 88° W. and N. 60° W.; a few trend about N. 75° E. The dominant set of joints on this flank of Shay Mountain trends N. 65° W. The copper minerals and the accompanying radioactivity are concentrated north of one major joint which trends about N. 88° W. and dips 60° northward (fig. 38). South of this joint the rock is devoid of copper minerals and the radioactivity does not rise above the background count. North of this joint, copper minerals are abundant and the radioactivity is three times as much as the background count. Other joints in this mineralized part of the mine are coated with copper minerals; locally they are concentrated along the intersection of several joints (fig. 38).

Samples from several of the localities that indicated abnormal radioactivity were submitted for chemical analysis. The results are given in table 5.

TABLE 5.—*Analyses, in percent, of samples from Tuffy Copper mine*

[Analysts: S. P. Furman, R. P. Cox, James Wahlberg, and E. C. Mallory, Jr.]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate	Copper
Laboratory	Field					
219063	Wa-48a	0.002	0	0.1	0.2	2.96
219064	Wa-48b	.001	0	.1	.1	5.92
219065	Wa-48c	.002	0	.1	.2	1.99

The relations in the Tuffy Copper mine (p. 104) suggest that copper minerals as well as some radioactive material were leached from overlying units (sandstone beds in the Salt Wash Member of the Morrison Formation?) by ground water which then percolated downward through joints. The copper minerals and the associated radioactive material were then redeposited along the joints and in adjacent strata.

SALT WASH MEMBER OF THE MORRISON FORMATION

The Salt Wash Member of the Morrison Formation includes many lenticular sandstone beds, several of which contain all the known uranium-vanadium deposits in the Abajo Mountains area.

The sandstone beds range from moderate grayish yellow (5*Y* 7/2) to light gray (*N* 8); they are massive and intricately crossbedded, and are composed chiefly of fine to coarse grains of quartz and minor amounts of microcline and chert. Plant remains are common and include both carbonized and silicified wood. The carbonized material appears as specks and fragments disseminated through the sandstone. The silicified wood, also scattered irregularly, ranges in size from small fragments to logs as much as 15 feet long and 2 feet in diameter (fig. 28).

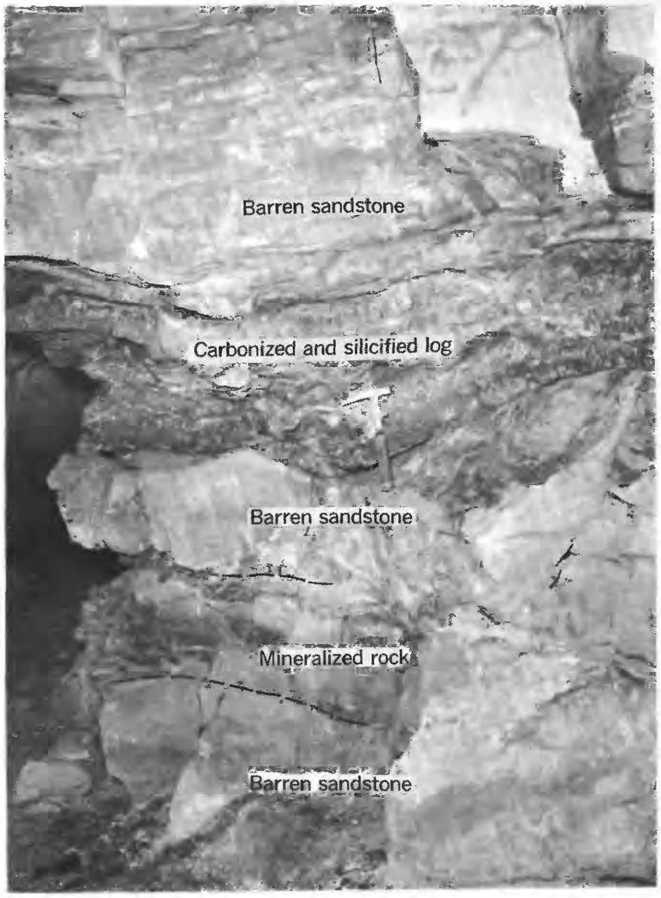


FIGURE 28.—Carbonized and silicified log in the Salt Wash Member of the Morrison Formation exposed at portal of one of the mines on the southwest flank of Shay Mountain. Part of a tabular ore body is exposed below the log.

The basal contact of the sandstone lenses is undulatory, and in places small channels have been cut in the underlying claystone (fig. 8). These channels, filled with material that appears identical in all respects to the sandstone away from channels, locally contain uranium-vanadium deposits.

Only a few of these channels are well enough exposed to permit study. In general, they seem to be symmetrical in outline, to be between 200 and 300 feet wide, and to be cut 5 to 25 feet into the underlying claystone. Their length is unknown.

Though all seven or eight sandstone beds in the Salt Wash can be considered as possible host rock for uraniferous deposits, some beds can be singled out that are more likely to contain mineralized deposits than others. These beds, called ore-bearing sandstone, are about 135 feet and 285 feet above the base of the Salt Wash (fig. 9). Commonly the deposits are either in channel fill at the base of these favorable sandstone beds, or are scattered irregularly through them. This latter situation is common where several of the sandstone beds have coalesced to form one very thick layer.

TYPES OF ORE BODIES

Two types of ore bodies can be recognized in the sandstones of the Salt Wash Member: small oval-shaped bodies that are irregularly distributed through the host rock, and flat tabular bodies that extend laterally for several hundred feet. Although the shapes of the ore bodies differ, both are alike in other respects. Most have a vanadium-to-uranium ratio of about 10 : 1, although locally it is as high as 20 : 1. The calcium carbonate content is high and averages about 10 percent, although it ranges from 1 to 19 percent. Many of the small ore bodies, therefore, are on the economic borderline because of their low uranium and high carbonate contents.

OVAL-SHAPED ORE BODIES

The small oval-shaped ore bodies are about 10 feet wide, 3 feet thick, and about 25 feet long, and commonly appear as medium light-gray (*N* 6) to light-gray (*N* 7) elongate masses parallel to the bedding planes of the sandstone. No pattern is apparent in their distribution. In a few places they form clusters, in which individual ore bodies are joined by thin mineralized seams of rock. Elsewhere these ore bodies are completely isolated from each other and are surrounded by barren strata.

Each of these ore bodies consists of sandstone that has been impregnated by uranium and vanadium minerals. The localization of the ore minerals seems to be independent of grain size, for the ore bodies are in sandstone that ranges from fine to coarse grained. In several places, the rims of these ore bodies cut across the crossbedding planes of the sandstone and seem to be unaffected by them (fig. 31). In other ore bodies, the margins extend outward along the crossbedding planes to create the effect of narrow lateral wings. Locally, considerable carbonaceous matter, as specks and fragments of carbonized wood, is scattered through the ore body. Elsewhere in the same sandstone, similar carbonaceous material is widespread but the surrounding rock is barren.

The ore bodies are cut by fractures that are coated with yellow metatyuyamunite where they pass through the ore body.

The uranium-vanadium is concentrated near the center of these ore bodies and decreases toward the margins, which invariably are weakly mineralized. Strata a few feet from the edge of the ore bodies are barren. Samples Wa–28a and Wa–28b of table 6 exemplify this localization; Wa–28b was collected near the center of an ore body, whereas Wa–28a was collected near the margin.

TABLE 6.—*Analyses, in percent, of samples from small discrete oval-shaped ore bodies*

[Analysts: James Wahlberg, Mary Finch, W. P. Goss, J. D. Schuch, S. P. Furman, and C. G. Angelo]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate	Type of sample
Laboratory	Field					
219019	Wa–23b	0.10	0.12	3.00	5.94	Grab.
219020	Wa–23c	.014	.015	.58	11.19	Channel.
219004	Wa–28a	.091	.11	.87	12.36	Grab.
219005	Wa–28b	.28	.32	3.22	10.89	Do.

This localization of the ore minerals and the small size of the ore bodies create an unusually difficult mining problem. Commonly much barren matter is mixed with the mineralized rock during the mining of these small ore bodies. In most places this mixture is far below the minimum standards established by the Atomic Energy Commission. The mineralized rock must be separated from the barren rock and, in the Abajo Mountains area, this has been done, at times, by hand.

Locating and mining the discrete oval-shaped ore bodies is a complex problem, for it is not always possible to determine from the outcrop the extent of mineralized rock. For example, the ore bodies in the Shay Mountain deposit penetrated by adits 4, 5, and 6 (pl. 5) are clearly oval shaped and trend either north west (adit 4) or west (adits 5 and 6). The mine maps show that the rock beyond the ore bodies was barren. The mine operator, after he has gone through the ore body, is faced with a difficult choice. Should he continue exploration in the hope of finding another ore body, or should he stop? Most operators continue to drift at least a short distance into the barren rock.

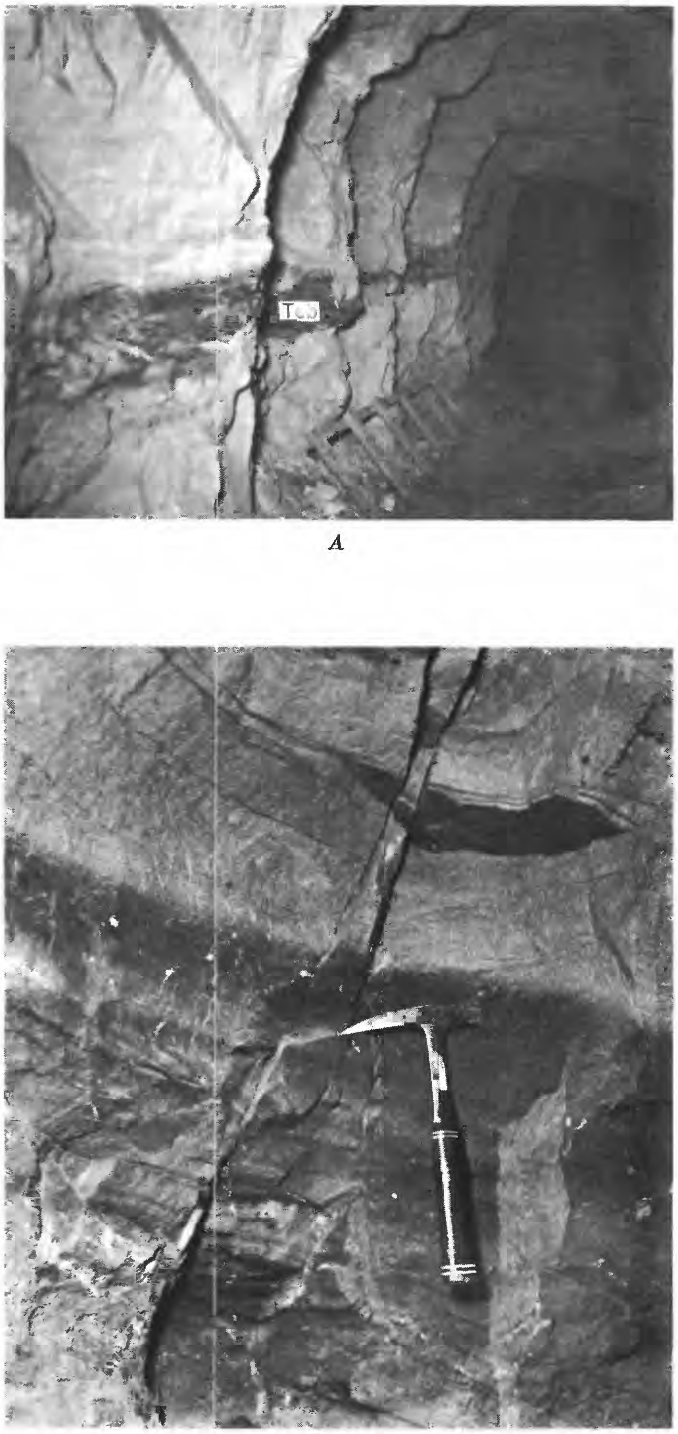
In the Abajo Mountains area, most of the mining has been an attempt to locate these small ore bodies; because they are so erratically distributed and so unrelated to any specific geologic feature, it is impossible to predict their location or extent. A drill hole might happen to penetrate one of a cluster, but a search for individual ore bodies by a general drilling program seems uneconomical. The only certain way to locate and mine each of these bodies is to strip the entire deposit. In view of the small size of the ore bodies, their wide spacing, and their low uranium-vanadium content, stripping does not seem warranted under current (1959) economic conditions.

TABULAR ORE BODIES

Only a few tabular ore bodies have been found. In general, they are about 30 feet wide, 3 feet thick, as much as 600 feet long, and appear as dark-gray (*N* 3) to light-gray (*N* 7) flat, tabular ribbonlike masses generally parallel to the bedding planes (fig. 29*A*).

Where a tabular ore body is exposed in a mine, it forms a mass of mineralized rock that in some places conforms closely to the bedding planes and in others cuts across them (fig. 29). The body thickens and thins erratically; and in a few places pinches out. Commonly it begins again in a lateral distance of a foot or two as a thin edge which thickens rapidly (fig. 34). In many places the strata directly above and below the ore body are barren, and the contact between mineralized and barren rock is sharp or gradational over an inch or less (fig. 29*B*). Elsewhere the strata adjacent to the ore body are weakly mineralized in a zone about 3 feet thick. Small dark-gray mineralized masses are scattered irregularly through the lighter barren rock and the zone is mottled (fig. 30). Miners refer to the zone as "leopard ore."

Although the tabular ore body is generally parallel to the bedding planes—it probably was localized in part by these planes—the crossbedding planes, at least locally, seem to have determined the concentration of the ore minerals. For example, the crossbedding planes in the ore body are commonly accentuated by dark streaks which represent greater concentrations of uranium and vanadium minerals (fig. 30). Similarly in the mottled zone, the darker



A

B

FIGURE 29.—A tabular ore body. *A*, Tabular ore body (Tob) exposed in mine. *B*, Distinct contact between the top of the ore body and the overlying barren rocks. In this locality the mineralized strata are collinear with the crossbedding planes; elsewhere they are not.

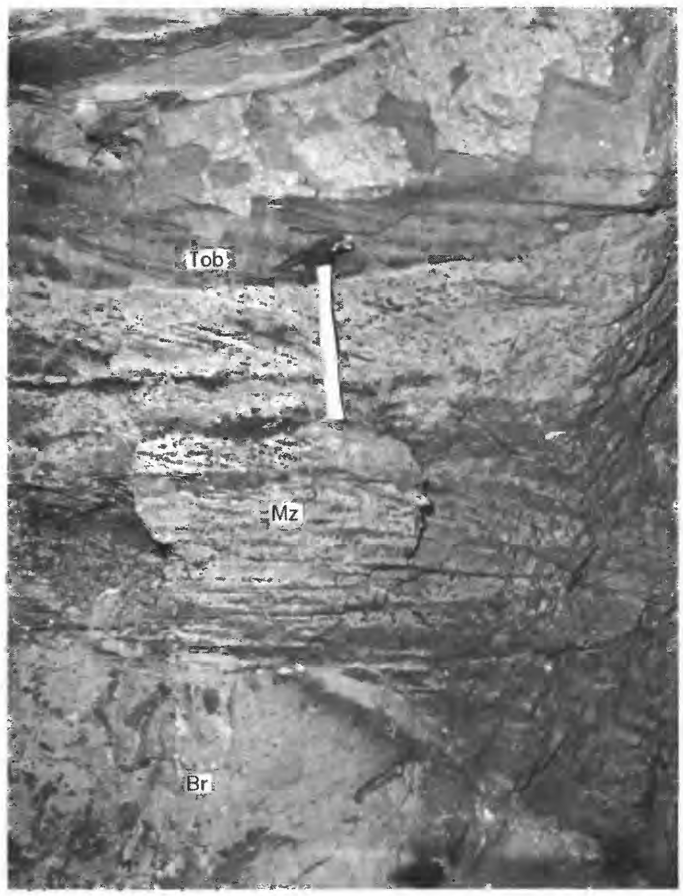


FIGURE 30.—Relations of part of a tabular ore body to the mottled zone. The tabular ore body (Tob) is in sharp contact with the underlying mottled zone (Mz), which grades into barren rock (Br). Note the accentuation of the crossbedding planes in both the ore body and the mottled zone by concentrations of uranium and vanadium minerals (dark-gray streaks).

mineralized masses are elongated parallel to and along the crossbedding planes (fig. 30). In contrast there are a few places where a tabular ore body ends abruptly, cutting across both bedding and crossbedding planes. Commonly the contact between mineralized and barren rock is sharp and distinct, and appears as a curved plane or roll (fig. 31).

Small accumulations of carbonized wood fragments are common both in the ore body and at a distance from it. Many of these accumulations contain angular to subround fragments of claystone and siltstone in addition to the carbonized material.

The logs that are scattered irregularly through the ore-bearing sandstones are, in general, mineralized when they are in a mineralized zone, but are barren or weakly mineralized beyond the limits of the mineralized zone. In one locality, part of a log lay within a tabular ore body and formed a high-grade deposit of uraniferous ore. In contrast, that part of the log beyond the limit of the ore body was barren.

Most of the fractures in these ore bodies are joints, but in one locality a fault that cuts and displaces a tabular ore body (fig. 32) suggests that the ore bodies antedated the fractures, which were probably formed during the emplacement of the intrusions. If so, the ore bodies were in existence before the Abajo Mountains were formed.

Analyses of samples from various parts of a tabular ore body indicate high concentration of the uranium and vanadium minerals in the center of the ore body and low concentration along the edges (table 7).

FIGURE 31.—Bedding planes cut by a roll of mineralized rock. Mineralized material is dark gray; weakly mineralized to barren strata are light gray. Hammer is along curving edge of roll.

TABLE 7.—*Analyses, in percent, of samples from a tabular ore body*

[Analysts: James Wahlberg, Mary Finch, W. D. Goss, J. P. Schuch, S. P. Furman, and C. G. Angelo]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate	Sample location
Laboratory	Field					
219028	Wa-31c	0.012	0.013	0.51	3.15	Mottled zone.
219029	Wa-31d	.29	.36	3.39	1.20	Ore body.
219030	Wa-31e	.051	.060	5.49	.66	Edge of roll.
219031	Wa-31f	.002	0	.53	3.15	Beyond roll.

The localization of the tabular ore bodies cannot be related unequivocally to any specific geologic feature. Because most of the mineralized exposures are in thick sandstone layers, it would seem that a thick sandstone was necessary for the gross localization of the deposit. Finely disseminated carbonaceous material in the interstices of the sandstone may have played a role in the precipitation of the ore minerals, although much carbonized material is in barren rock as well. Carbonized logs locally are important but are ore bearing only where they intersect mineralized rock. The carbonized log pictured in figure 28, for example, does not seem to have influenced the location of the

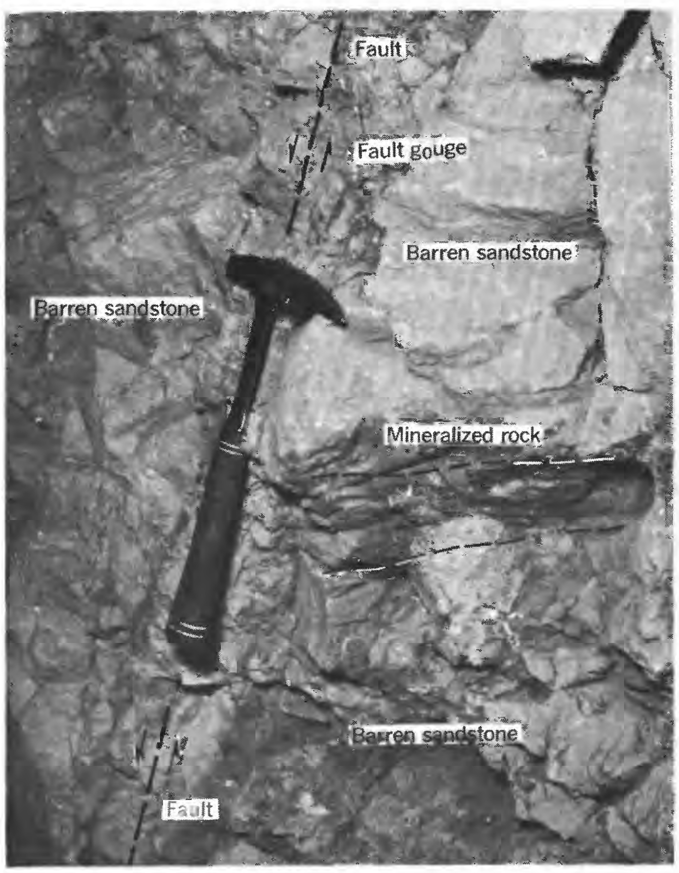


FIGURE 32.—Thin seam of mineralized rock displaced by north fault of the small graben shown on map of adit 3 on plate 5.

underlying ore body. It seems clear, also, that the ore bodies are independent of the fractures; in fact, the ore bodies seem to antedate the fractures (p. 90). Although the mineralized sandstone seems similar to the unmineralized rock in lithology, grain size, and cementing agents there may be some minor differences. Possibly both the porosity and permeability of the mineralized sandstone differed from that of the unmineralized rock. If the difference at the time of invasion by the ore solutions was marked, this may have determined the localization of the ore minerals.

URANIUM-VANADIUM DEPOSITS

In the Abajo Mountains area uranium-vanadium deposits are localized in six specific localities: at Shay Mountain, in Harts Draw, at the Lakes Claim, along Shay Road, at Robertson Pasture, and at the Sunshine Mining claim.

SHAY MOUNTAIN DEPOSIT

The uranium-vanadium deposit on Shay Mountain crops out on the southwest flank of the mountain in the NE¼ sec. 14, T. 33 S., R. 21 E. (unsurveyed).

The deposit was found originally in 1944 by geologists of the Geological Survey. In 1951, J. G. and G. L. Shumway of Blanding, Utah, staked the area as the Blue claims, constructed an access road across Indian Creek to the deposit, and began to mine the ore. The property was subsequently leased to the E. Standard Co. of Salt Lake City, Utah, who mined the property for a short period in 1956. Since then the property has reverted to the Shumways.

At least 16 distinct mineralized exposures are in sandstone beds near the middle and upper parts of the Salt Wash Member of the Morrison Formation (pl. 5). In general, three sandstone beds, separated by claystone and siltstone, can be distinguished. The general position occupied by each of the sandstone beds is represented on plate 5 by one of the three access roads. The lower road to mineralized exposures 1 through 8 ascends through the lower sandstone. The middle road to mineralized exposures 12, 13, and 14 is along the base of the middle sandstone, and the upper road to mineralized exposure 16 is along the base of the upper sandstone ledge. In a few places, as the sandstone beds are traced laterally, the intervening claystone-siltstone sequence becomes sandy and changes imperceptibly into sandstone. In these localities, a thickened sandstone ledge is found which cannot be subdivided. This formation of a thick sandstone bed has happened near the west edge of the mineralized area (plate 5) and mineralized exposures 9, 10, and 11 are in a 60-foot thick sandstone that can be traced laterally into a claystone.

Each of the sandstone beds is lenticular, and thickens and thins erratically. In general, they range in thickness from 10 to 40 feet, the mineralized exposures being in the thickened part of the sandstone beds.

Most of the mineralized exposures are classed as small oval-shaped ore bodies, although exposure 1, penetrated by adits 1, 2, and 3, may represent a tabular ore body. Some of the oval-shaped ore bodies are surrounded by barren strata (examples are mineralized exposures 3, 4, 5, 12, 13, 14, and 16; see pl. 5). Others are attached to one another by thin bands of mineralized rock and form clusters. One such cluster, at the east edge of the mineralized area, contains exposures 1 and 2 (pl. 5). Another cluster at the west edge of the area includes mineralized exposures 6, 7, 8, 9, 10, 11, and 15.

The tabular ore body(?) intersected by adits 1, 2, and 3 is estimated to have been, before mining, about 100 feet long, 20 feet wide, and 3 feet thick. For most of its extent it appears as a continuous undulatory band of mineralized rock that thickens and thins irregularly. Near the edges, the ore body splits and forms several seams of mineralized rock separated by weakly mineralized or barren strata. The ore body parallels the bedding planes, and the ore minerals are localized either in a crossbedded fine-grained sandstone or, in a few localities, in small thin conglomerate lenses near the base of the ore body.

The sandstone beds have been cut by two sets of joints that are part of the system of dip and strike joints which encircle Shay Mountain. One set of joints trends from N. 50° W. to N. 70° W.; the other trends from N. 10° E., to N. 50° E. (pl. 5).

In one locality, the sandstone bed that contains the tabular ore body is displaced by a small graben (adit 3, pl. 5). The offset along the south fault is about 15 feet; the offset along the north fault is not known. The two faults trend N. 65° to 70° W., and they parallel, therefore, the joint set that trends N. 50° W. to N. 70° W. The faults parallel the joints, and therefore both were probably formed synchronously as a result of the emplacement of the Shay Mountain stock(?). The implication is that the ore bodies were emplaced before the Abajo Mountains were elevated.

This displacement of an ore body, however, can be interpreted in another way. A sandstone that contained a favorable zone for the localization of uranium-vanadium minerals may have been faulted, and the zone displaced. In time, ore solutions percolating through the host sandstone may have precipitated ore minerals only in the favorable zone. The final result would appear as an ore body apparently cut and displaced by a fault.

The field evidence, therefore, is tenuous and open to more than one interpretation. In my judgment the ore body was cut and offset by a fault. If the ore solutions moved into the sandstone after it was fractured, it seems reasonable to infer that both faults and joints would have been used as channelways. But where the ore body is cut by joints, the mineralized rock appears indifferent to them; the ore body can be traced as a smooth unbroken line across the joints, and does not extend into them. Nowhere do the dark-gray uranium-vanadium minerals of the ore body extend as minor projections either up or down any of the fractures that cut the ore body. This absence does not mean that the fractures near the ore body are completely free of uraniferous material. Locally some of the fractures contain small amounts of secondary yellow uranium-vanadium minerals, such as metatyuyamunite, but these minerals are interpreted as having formed long after the emplacement of the ore body, and to have stemmed from circulating ground water.

HARTS DRAW DEPOSIT

The uranium-vanadium deposit in Harts Draw consists of scattered mineralized exposures in the W½ sec. 2 and in the center of the N½ sec. 10, T. 33 S., R. 22 E. Both oval-shaped and tabular ore bodies are represented.

The deposit was first found in 1944 by geologists of the Geological Survey. In 1948–49, L. H. Smith reexamined the area and staked claims across the mineralized exposures. Subsequently, Smith and a group of his associates formed the Utah-Colorado Development Co. and began to exploit the area. Roads were built to mineralized deposits, and the more favorable areas were explored by drilling. By 1954, most of the small deposits had been mined out, and exploration had delineated parts of two tabular ore bodies. In 1956, the property was leased to the Clontz Construction Co. who continued both the mining and the exploration program. In 1957, the property was leased to L. H. Smith.

Most of the small mineralized deposits consisted of oval-shaped ore bodies and each of the sandstone beds of the Salt Wash Member contained at least one such body. The ore bodies seemed to be distributed at random, most being concentrated in those ore-bearing sandstone beds about 185 feet above the base of the Salt Wash Member (fig. 9).

The small size and erratic distribution of these oval-shaped ore bodies discouraged any detailed search for them. After the easily found bodies were mined out, all further efforts were directed to developing the tabular ore bodies.

The two tabular ore bodies are in a sandstone bed about 40 feet thick and about 190 feet above the base of the Salt Wash Member. An attempt was made by drilling to delineate and trace the ore bodies; the greatest amount of work has centered about the south ore body (fig. 33).

The two ore bodies are in the center of the N½ sec. 10, T. 33 S., R. 22 E., and are separated by about 400 feet of barren rock (fig. 33). The north ore body trends about N. 60° E., and has been traced about 250 feet from its outcrop by drilling. It may curve sharply to the southeast and extend along a trend of about S. 40° E., for at least an additional 250 feet. This tabular ore body is estimated to be about 40 feet wide, and to average 3 feet in thickness. As of the spring of 1958, Smith, the lessee, had drifted about 160 feet into the ore body.

A sample of mineralized rock was identified by E. J. Young (written communication, 1959) as follows:

> * * * This is a gray, very fine-grained sandstone containing thin yellow-green coats of metatyuyamunite. In view of the high V : U ratio (10 : 1) there may be a vanadium mineral or minerals present, but none were detected in the X-ray diffractometer. Carbonaceous material present in the sample may play host to some of the vanadium, however.

The south tabular ore body trends about S. 85° E. from its outcrop (fig. 33). It has been traced for about 625 feet by drilling, and it may continue for a considerable distance beyond that point. It is about 50 feet wide and averages 2 feet in thickness. This ore body also curves sharply to the southeast and trends about S. 40° E. It is not known whether this sudden change of trend of both ore bodies to the southeast is significant.

The Indian Creek No. 2 mine follows the south ore body for about 280 feet; details of the ore body are shown in the sketch of the north wall of the mine in figure 34. Exposures of the south ore body in the mine furnished most of the data in the description of a tabular ore body on page 88–91.

The ore body is in one of the ore-bearing sandstone beds in the Salt Wash Member. In detail the uranium-vanadium minerals seem to have been most selective, only occurring in certain parts of the ore-bearing sandstone, and these parts seem identical to the barren parts of the sandstone. Thus, the ore body contains many fragments of carbonized and silicified wood, as well as logs of silicified wood, but the fragments and logs apparently have not localized the ore body. Similarly, the ore body cannot be related to any concentrations of clay galls or claystone splits. Identical sedimentary structures can be found in both barren and mineralized rock. Although the ore body is cut by many fractures it is nowhere displaced (fig. 34); possibly the ore body antedated the fractures (p. 90).

The most reasonable explanation for the localization of the ore bodies seems to rest on minor favorable conditions of porosity and permeability coupled with concentrations of finely disseminated carbonaceous material. The oval-shaped ore bodies probably represent local areas marked by such favorable conditions, whereas the longer, more continuous tabular ore bodies represent a relatively extensive favorable zone.

LAKES CLAIM DEPOSIT

A group of mineralized exposures in the SW¼ sec. 10, T. 33 S., R. 22 E. (unsurveyed), constitutes a small deposit known as the Lakes Claim.

The area was first claimed in 1953 by A. J Redd and his son W. H. Redd. The Redds built roads and began a limited exploration program, but found no mineralized ground. In 1956, the Redds were joined by G. M. Palmer and M. Nelson and together they mined out most of the mineralized exposures.

Of the six mineralized exposures, most are grouped in the east part of the area (fig. 35*A*). The host rock, a sandstone bed about 180 feet above the base of the Salt Wash, is tentatively correlated with the sandstone that contains the tabular ore bodies of the Harts Draw deposit.

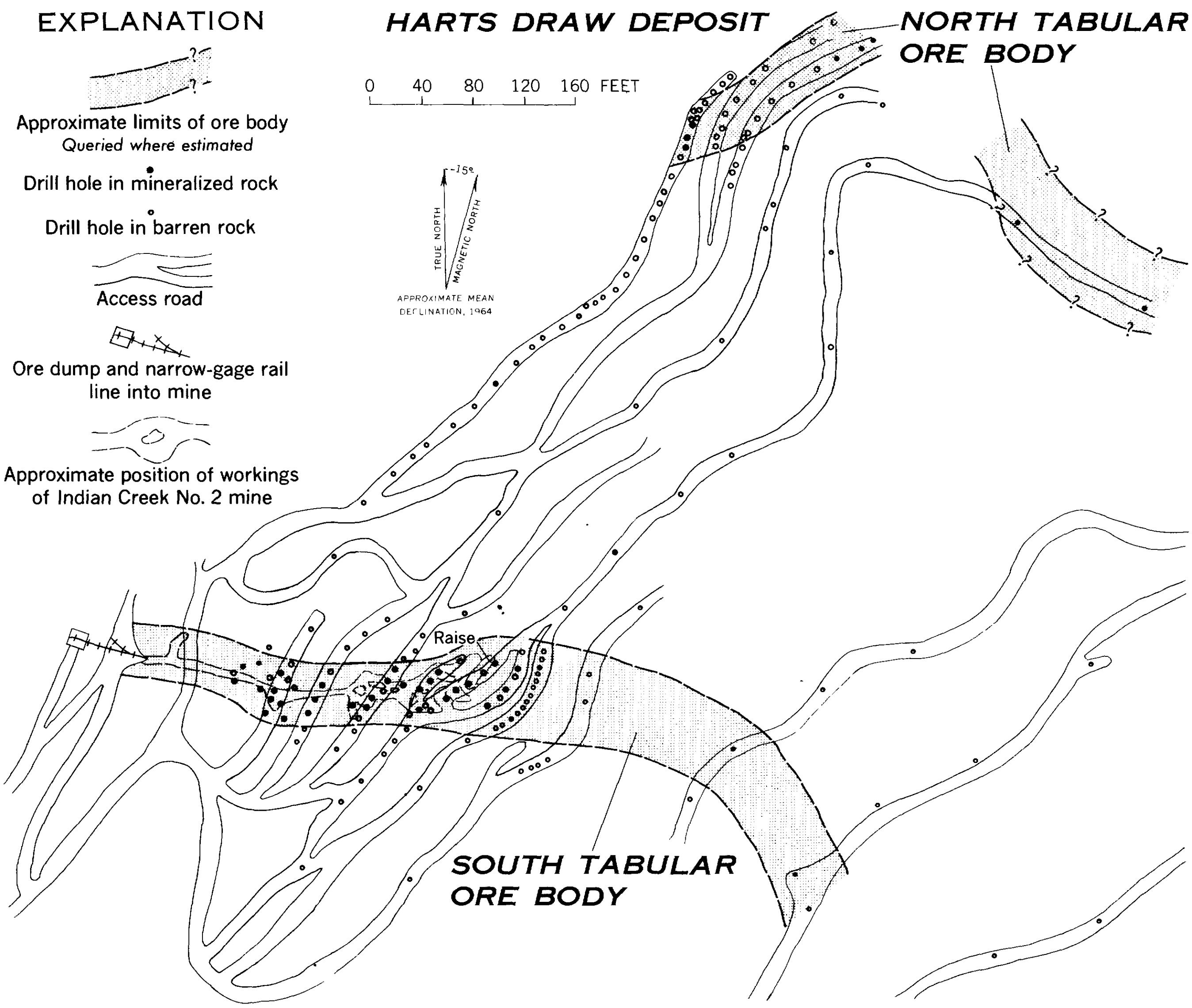


FIGURE 33.—Trend and general pattern of the two tabular ore bodies in the Harts Draw deposit.

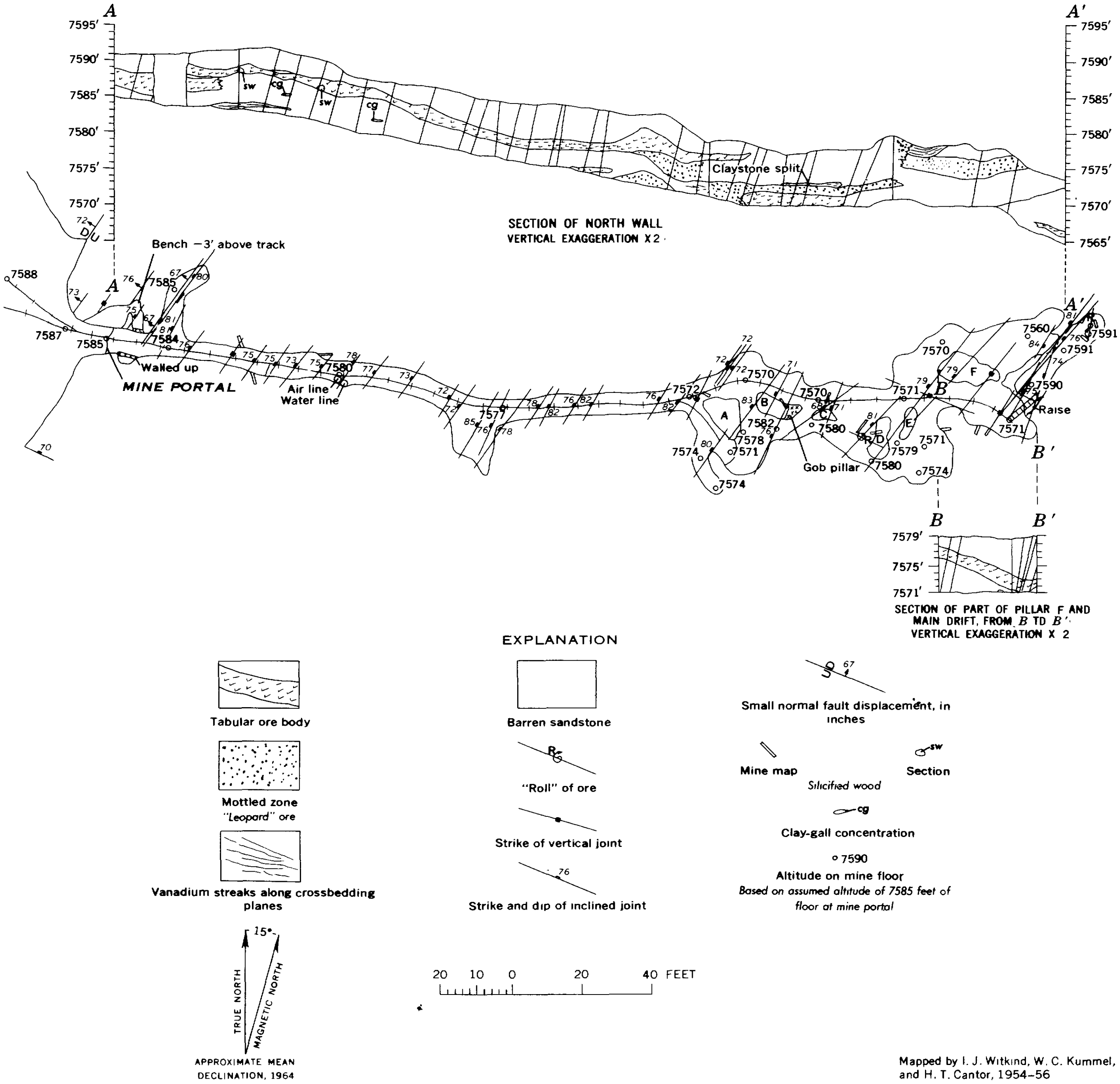


FIGURE 34.—Mine map and sections of the Indian Creek No. 2 mine, San Juan County, Utah. Note that the ore body thickens and thins, and cuts across joints, clay-gall concentrations, silicified wood, and claystone splits.

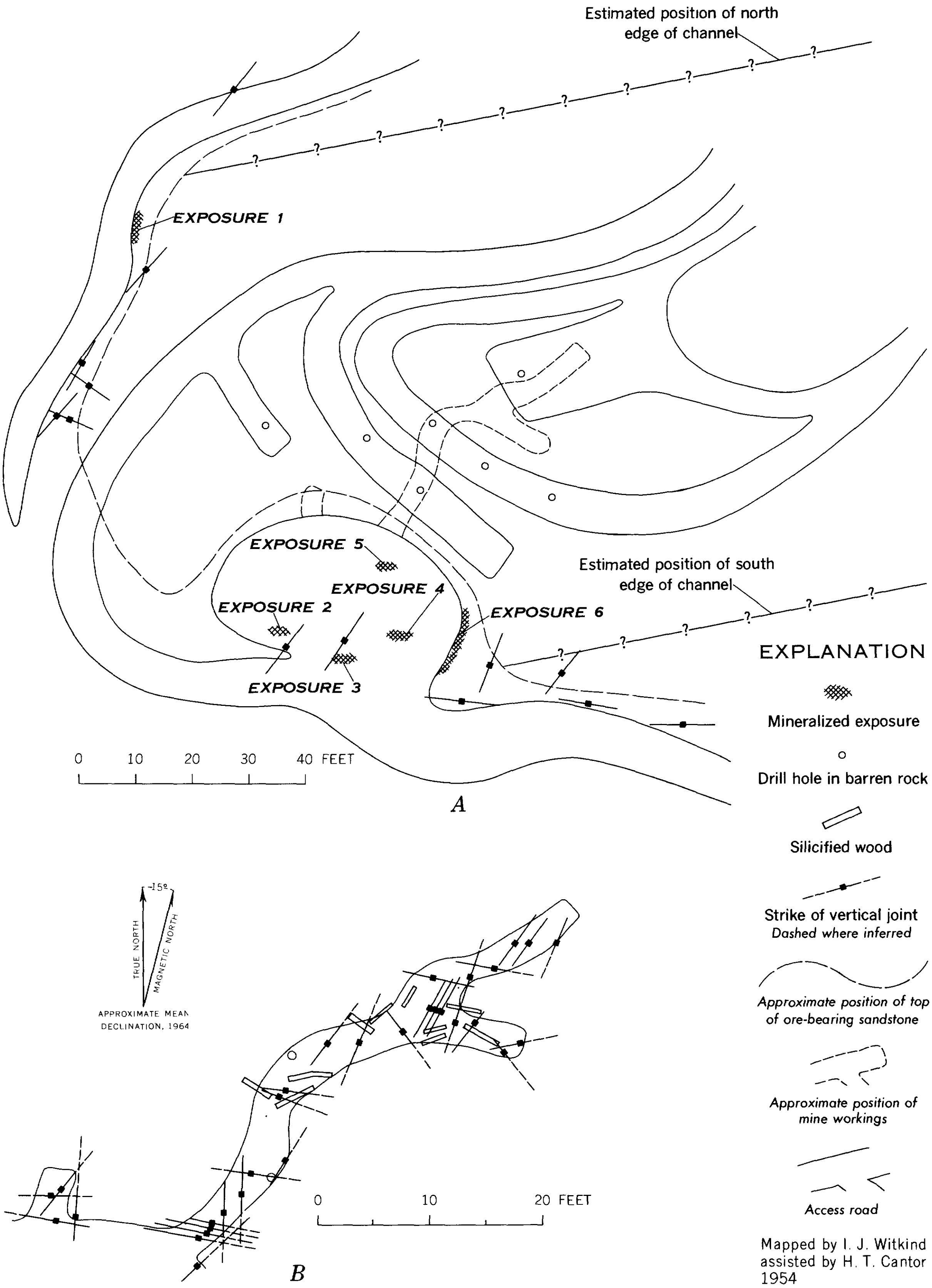


FIGURE 35.—Lakes Claim deposit. *A*, Access roads and mineralized exposures. *B*, Mine map of Lakes Claim.

The host sandstone is a pale grayish-orange (10*YR* 7/2) massive crossbedded fine- to medium-grained bed about 15 feet thick which contains a few small lenses of conglomerate near its base. The sandstone, for part of its extent, fills a channel which trends about N. 80° E. (fig. 35*A*) Colluvium and debris from the access roads conceal much of the channel, but it is estimated to be about 180 feet wide and to have been scoured about 10 feet into the underlying claystone beds. Its length is not known. All the mineralized exposures, which have since been mined out, were in the channel fill.

Of the six mineralized exposures, five were classed as oval-shaped ore bodies; these average 15 feet in length, 3 feet in width, and 2 feet in thickness. The sixth was a flat tabular ore body about 50 feet long, 35 feet wide, and 2 feet thick.

The mineralized exposures ranged from medium light gray (*N* 6) to light gray (*N* 7). Locally, small specks of yellow metatyuyamunite dotted the surfaces of the mineralized exposures.

Samples from both an oval-shaped and a tabular ore body have been analyzed to show the relative uranium-vanadium content (table 8).

TABLE 8.—*Analyses, in percent, of samples from the Lakes Claim deposit*

[Analysts: James Wahlberg, Mary Finch, W. D. Goss, J. P. Schuch, S. P. Furman, and C. G. Angelo]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate	Sample location
Laboratory	Field					
219024	Wa-32a	0.035	0.040	0.41	14.64	Tabular ore body.
219025	Wa-32b	.075	.083	1.50	16.59	Oval ore body.

SHAY ROAD DEPOSIT

The Shay Road deposit, in the SE¼ sec. 17, T. 33 S., R. 22 E. (unsurveyed), contained a small oval-shaped ore body exposed in a road cut. The area was claimed in 1956 by A. J. Redd, who shortly thereafter mined out the mineralized exposure. A small amount of exploratory drifting was done in the same mine in an unsuccessful attempt to locate another ore body.

This part of the area is thickly covered with colluvium, and hence it is uncertain which of the ore-bearing sandstone beds of the Salt Wash contained the mineralized exposure; probably the host sandstone is near the base of the Salt Wash.

The mineralized exposure consisted of a segment of an oval-shaped ore body, part of which had been destroyed during the construction of the road. The exposure appeared as a medium light-gray (*N* 6) mass of sandstone surrounded by pale grayish-orange (10*YR* 7/2) barren rock. Small specks of metatyuyamunite(?) were on the face of the mineralized exposure, especially along the small fractures that cut the ore body. It is estimated that the original ore body was about 10 feet long, 3 feet wide, and 3 feet thick.

ROBERTSON PASTURE DEPOSIT

The Robertson Pasture deposit crops out along the east valley wall of Indian Creek in the NW¼ sec. 20, T. 33 S., R. 22 E. (unsurveyed). It contains five mineralized exposures (fig. 36).

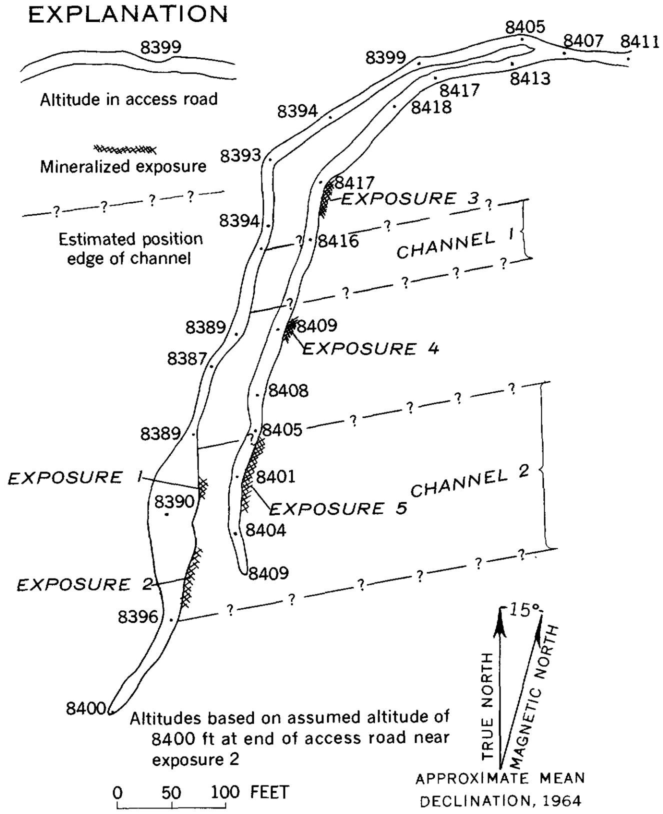


FIGURE 36.—Access roads and mineralized exposures, Robertson Pasture deposit, San Juan County, Utah.

The deposit was staked in 1951 by Wallace and Pete Bailey, who constructed roads and began mining operations. In 1955, the deposit and the adjacent claims were leased to Adolph Kaufman, who undertook a program of rim-stripping south of the deposit. No new mineralized ground was discovered. As of the spring of 1958, the deposit was being worked by R. L. Stadter, V. L. Hobbs, and R. Elder, who had leased the property from R. D. and Nadine Bailey.

The deposit is covered with dense vegetation and colluvium, and good exposures are rare. In general, the mineralized exposures are localized in two ore-bearing sandstone beds that are about 200 feet above the base of the Salt Wash Member. Each bed ranges in thickness from 10 to 15 feet. Locally these two sandstone beds merge to form a single bed about 30 feet thick. The sandstone is cut by joints that trend from N. 20° E. to about N. 55° E., and dip 65° to 70° southward.

Two channels at the base of the lower sandstone are thought to be parallel and to trend about N. 80° E. (fig. 36). The north channel, referred to as channel 1, is about 60 feet wide and has been scoured about 10 feet into the underlying claystone. No mineralized exposures were found in the channel fill. The south channel, known as channel 2, is about 160 feet wide and is thought to have been scoured about 15 feet into the underlying claystone (fig. 8*A*). Three mineralized exposures (1, 2, and 5, fig. 36) are in the channel fill.

The relations of the mineralized exposures to the channel fills are puzzling. Of the five mineralized exposures, three (exposures 1, 2, and 5) are within the confines of channel 2 (fig. 36). The remaining two (exposures 3 and 4) flank channel 1 and are outside the channel fill. One explanation involves the possible continuity of the sandstone. Near channel 2, the two ore-bearing sandstone beds have merged to form one thick sandstone, part of which fills the channel. Near channel 1, the two ore-bearing sandstone beds are separated by claystone, and the mineralized areas are exposed only in the upper sandstone above the channel.

The mineralized exposures can be classified as four oval-shaped ore bodies (exposures 1, 3, 4, and 5) and one modified tabular ore body (exposure 2). All appear as medium light-gray (*N* 7) masses of sandstone surrounded by pale grayish-orange (10*YR* 7/2) barren rock. Locally a few specks of yellow metatyuyamunite(?) are along fractures that cut the ore bodies.

Access roads have been built to the mineralized exposures (fig. 36) which have been mined, chiefly by bulldozing away the barren rock.

The oval-shaped ore bodies ranged in size from one that was 8 feet long, 3 feet wide, and 3 feet thick, to one that was about 40 feet long, 6 feet wide, and about 2 feet thick. These dimensions are based partly on preserved exposures, and partly on statements by Wallace Bailey, one of the original claimants. Remnants of the ore bodies are still preserved, and analyzed samples of these show the relative uranium-vanadium concentration (table 9).

Part of the tabular ore body (exposure 2) has been mined out, but it is estimated to have been about 60 feet wide, about 2 feet thick, and of unknown length. Locally the mineralized rock that forms the tabular ore body splits into thin seams separated by barren or weakly mineralized sandstone. Analyses of channel samples from a tabular ore body (table 10) show that in these localities the grade of the mineralized rock drops sharply, because of the presence of the sandstone splits. Sample Wa–23b was taken from a tabular ore body devoid of sandstone splits, whereas Wa–23c contained several sandstone splits.

TABLE 9.—*Analyses, in percent, of samples of oval-shaped ore bodies in the Robertson Pasture deposit*

[Analysts: James Wahlberg, Mary Finch, W. D. Goss, J. P. Schuch, S. P. Furman, and C. G. Angelo]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate	Sample location (fig. 36)
Laboratory	Field					
219018	Wa–23a	0.054	0.068	3.34	1.77	1
219023	Wa–23f	.12	.16	2.76	13.32	5

TABLE 10.—*Analyses, in percent, of samples collected from tabular ore body in the Robertson Pasture deposit*

[Analysts: James Wahlberg, Mary Finch, W. D. Goss, J. P. Schuch, S. P. Furman, and C. G. Angelo]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate	Remarks
Laboratory	Field					
219019	Wa–23b	0.10	0.12	3.00	3.00	No sandstone splits.
219020	Wa–23c	.014	.015	.58	11.19	Sandstone splits.

SUNSHINE MINING CLAIM

The Sunshine Mining Claim, near the center of the E½ sec. 26, T. 34 S., R. 21 E. (unsurveyed), contains several small mineralized exposures.

The deposit had been examined and a road had been built to it before 1944, when geologists of the Geological Survey examined the exposure In 1951, a claim was staked by Harry Laws, but no mining has been done.

The area is concealed beneath colluvium and exposures are poor. The deposit is within the Verdure graben, about 1,000 feet south of the North Verdure fault. Two small mineralized exposures are near the base of a massive crossbedded fine- to medium-grained sandstone, which is about 150 feet above the base of the Salt Wash Member.

The main mineralized exposure is classed as an oval-shaped ore body, about 10 feet long, about 3 feet wide, and about 2 feet thick. It appears as a medium-gray (*N* 5) mass of vanadiferous sandstone surrounded by light-gray (*N* 7) barren rock. Small specks of metatyuyamunite(?) are on the outcrop. A sample collected from the exposure indicates the uranium and vanadium concentrations (table 11).

About 50 feet north of this exposure is a small log of silicified wood, about 4 feet long and 6 inches in diameter, surrounded by a halo of vanadiferous sandstone.

TABLE 11.—*Analysis, in percent, of grab sample from mineralized exposure on Sunshine Mining claim*

[Analysts: S. P. Furman, R. P. Cox, and James Wahlberg]

Sample No.		Equivalent uranium	Uranium	Vanadium pentoxide	Calcium carbonate
Laboratory	Field				
219076	Wa-63	0.041	0.023	1.61	12.9

AGE OF THE URANIUM-VANADIUM DEPOSITS

The age of the uranium-vanadium deposits is suggested by the relations of the uraniferous ore deposits to the fractures. On Shay Mountain, a small graben displaces a tabular ore body (p. 91). Inasmuch as the faults that border the graben parallel the joints in this specific locality, faults and joints may have been formed synchronously and by the same forces—perhaps when the Shay Mountain stock (?) was being intruded. Because the ore body is displaced by the faults, it seems likely that the ore body antedates the faults, and the inference is strong that the ore deposits were established before the Abajo Mountains were formed. Although this offset in the ore body can be explained in another way (p. 91), other ore bodies (for example, in the Harts Draw deposit) also seem to have been emplaced and then cut by fractures.

I suggest, therefore, that the ore bodies were formed before the mountains were domed. Because the intrusions are tentatively dated as Late Cretaceous to early Eocene (p. 81), the age of the uranium-vanadium deposits must be considered as post-Late Jurassic (that is, post-Morrison Formation) and pre-Late Cretaceous.

FAVORABLE GROUND

Those areas underlain at shallow depth by the Shinarump Member of the Chinle, the Moss Back Member of the Chinle, and the Salt Wash Member of the Morrison must be considered as favorable ground. These units contain ore deposits in this and adjacent areas, and it is probable that they contain other ore deposits still concealed beneath colluvium or younger consolidated strata. Of the three units only the Salt Wash Member contains uranium-vanadium ore deposits in the Abajo Mountains area. The Salt Wash is considered, therefore, to be more likely to contain such deposits in the mapped area than the other two units.

Only six uranium-vanadium deposits are exposed in the Abajo Mountains area, and any delineation of a favorable zone based on such a small number has limited value. The deposits are so arranged, however, as to suggest some structural control, although it may be nothing more than a fortuitous grouping.

Five of the six deposits are exposed along the north flank of the mountains and form a cluster elongated to the northeast (fig. 37). These five deposits are crudely alined and trend about N. 70° E., almost parallel to the N. 65° E. trend of the Shay graben. If this trend of the deposits is projected to the northeast, beyond the limits of the mapped area, it alines with three major vanadium deposits—the Happy Jack deposit, the Frisco group, and the Sunset deposit (fig. 37)

This alinement of the uraniferous deposits, plus the parallelism with the Shay graben, may be fortuitous, but it may also indicate some fundamental structural control of the ore deposits localized in the Salt Wash Member. It has been suggested (p. 46) that the grabens are independent of the mountains, and were formed before the mountains were domed. The uranium-vanadium deposits may also predate the doming of the mountains (p. 98). Possibly the regional forces that formed the grabens also determined the localization of those uraniferous deposits in the Salt Wash Member. Until it can be ascertained whether this alinement of the uraniferous deposits is fortuitous or represents structural control, I suggest that a zone of favorable ground, trending N. 60° E., extends across the north flank of the mountains. This zone, about 3 miles wide, includes the five uraniferous deposits (fig. 37).

The uranium-vanadium deposits exposed indicate that any new deposits found in this zone probably will be widely separated, small, and of relatively low uranium and high carbonate content.

It has been postulated that a zone of favorable ground trends across the Elk Ridge area (fig. 37), southwest of the Abajo Mountains (Lewis and Campbell, 1964). This postulation is based on known uraniferous ore deposits, all of which are in Triassic sedimentary rocks. By contrast, my postulation of a zone across the Abajo Mountains area is based on ore deposits in Jurassic sedimentary rocks. Consequently it is uncertain whether the two zones are related. As drawn, a projection of the Elk Ridge zone would cross the south flank of the Abajo Mountains. But the trend of the east part of the Elk Ridge zone is vague and uncertain, and it could lie in any one of several directions (R. Q. Lewis , Sr., oral communication, 1956). A projection of the east part of the Elk Ridge zone to the northeast—instead of to the east—would aline it with the zone of favorable ground across the north flank of the Abajo Mountains (fig. 37).

OIL AND GAS POSSIBILITIES

After the discovery and development of the Aneth oil field southeast of the Abajo Mountains, interest spread to adjacent areas. By 1956 the search for possible oil structures had reached the broad plains south and east of the mountains, and in 1957 it moved into the mountains.

Three test holes were drilled in and adjacent to the Abajo Mountains area. All were dry, although there was a show of oil and gas in one.

The first well to be drilled in the report area was the J. G. Dyer Drilling Co's. Government 1 in the SW¼ sec. 19, T. 34 S., R. 22 E. (unsurveyed). It was collared in the Navajo Sandstone, was drilled about 2,079 feet, and bottomed as a dry hole in quartz diorite porphyry.

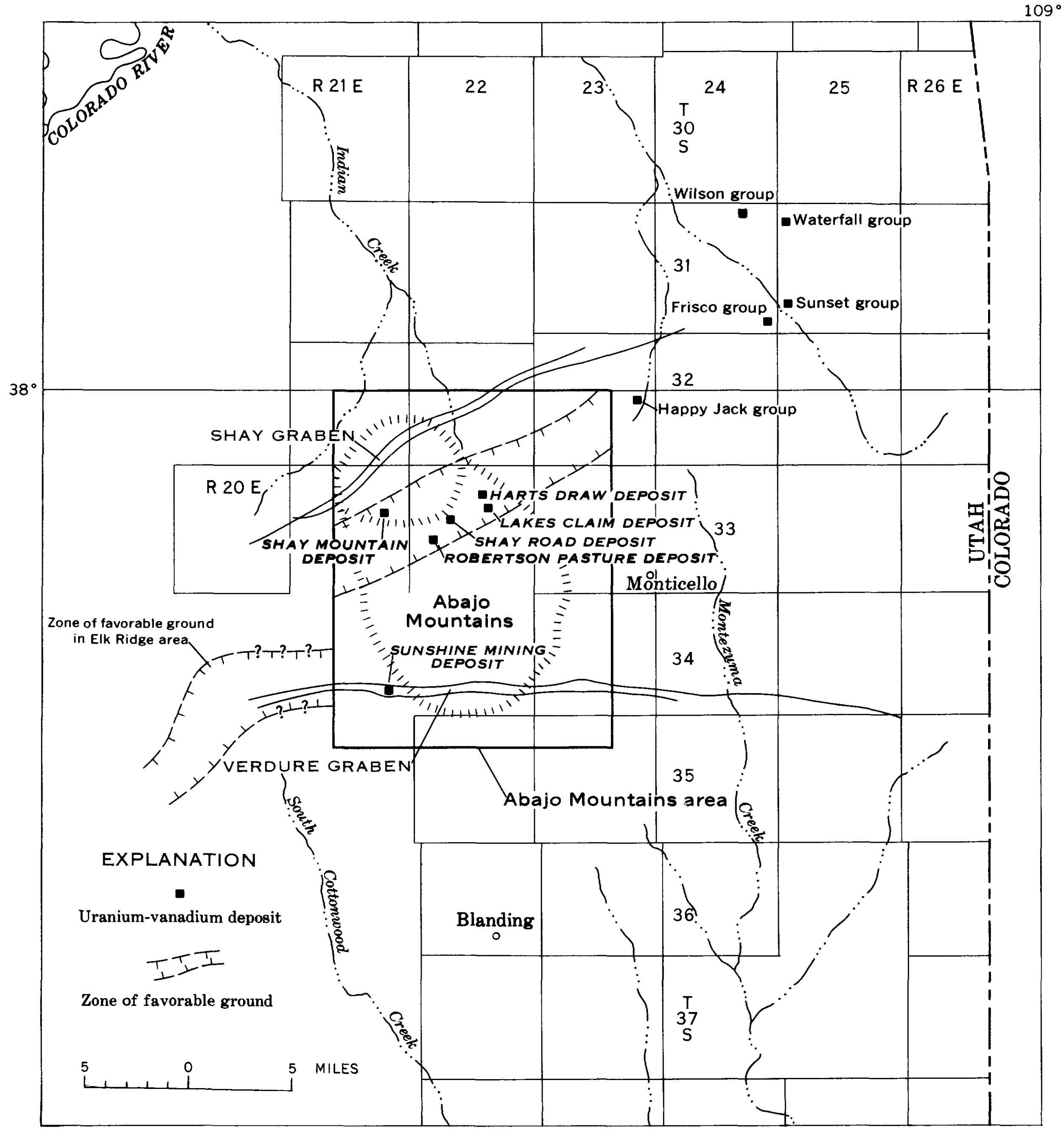


FIGURE 37.—Locations of the uranium-vanadium deposits in the Abajo Mountains area. All the deposits are in the Salt Wash Member of the Morrison Formation. (Also shown are several adjacent groups of deposits that are localized in the Morrison Formation and that may aline with the major grouping of the Abajo Mountain deposits.)

The well is reported to have penetrated the following units:

Unit	Thickness (feet)
Navajo Sandstone	285
Kayenta Formation	140
Wingate Sandstone	292
Chinle Formation (including Shinarump Member)	503
Moenkopi Formation	415
Intrusive body	444
Total depth	2,079

While the Dyer Drilling Co. was drilling its well, the Standard Oil Co. of California began a test well about 6 miles south of the south border of the report area. This well, known as Johnson Creek Unit 1, is in the SE¼ sec. 33, T. 35 S., R. 22 E. It was collared in the Dakota Sandstone, drilled 6,444 feet, and finally abandoned as a dry hole after it bottomed in evaporite of the Paradox Member of the Hermosa Formation. There were small shows of oil and gas in this well at a depth of about 6,100 feet, in the Bluff unit of the Paradox Member.

The well is reported to have penetrated the following formations:

Unit	Thickness (feet)
Dakota and Burro Canyon Formations	180
Morrison and Summerville Formations	915
Entrada Sandstone	135
Carmel Formation	100
Navajo Sandstone	545
Kayenta Formation	172
Wingate Sandstone	348
Chinle Formation	685
Moenkopi Formation	190
Cutler Formation (including Cedar Mesa Sandstone Member, Halgaito Tongue, and possibly the Rico Formation)	1,847
Hermosa Formation:	
Upper part	940
Paradox Member:	
Bluff unit	235
Desert Creek zone	108
Evaporite zone	44
Total depth	6,444

The third well, known as the Abajo Federal 1, was drilled by the Gulf Oil Co. at the very west edge of the mapped area in the NW¼ sec. 9, T. 34 S., R. 21 E. (unsurveyed). The well was collared in the Navajo Sandstone, and penetrated 4,605 feet before it was bottomed as a dry hole in the Hermosa Formation. No data are available as to the formations penetrated.

Although these three wells were dry, it seems likely that there will be other tests near the mountains, for there is considerable interest in this general region. Of the three wells, two penetrated strata that produce oil in adjacent areas, so it is known that the mountains are underlain by favorable host rocks. Further, parts of the mapped area may contain stratigraphic and structural traps. The necessary combination of favorable host rock and suitable traps seems to be present, therefore, in at least parts of the Abajo Mountains area.

The locality that seems most worthy of further exploration is near the Causeway, along the west edge of the mapped area (pl. 1). The apparent pinchout of certain units of the Carmel and Summerville Formations implies that an ancestral high may have persisted in this specific locality during part of Jurassic time (p. 83), but it is uncertain whether this ancestral high was active in the Paleozoic; if it was, stratigraphic traps may have formed around the flanks of this upland.

Structural traps may have been formed near the two grabens, and these localities seem worthy of geophysical examination. Further, suitable traps may exist where the stocks pushed up through the overlying sedimentary strata (Hunt, 1942, p. 203). Each stock is probably encircled by upturned beds. Oil and gas may well have migrated up certain of these beds and formed pools against the flanks of the stocks.

Other apparent structural traps are much less significant; for example, the Corral and Spring Creek anticlines (p. 58, 59) probably are formed by laccoliths. These anticlines are shallow features, and do not represent deep or significant structures.

One factor that may have great significance in the search for oil and gas pools near the Abajo Mountains is the possibility that these pools may have been shifted as a result of the emplacement of the stocks.

Locating these traps is likely to be difficult, time-consuming, and expensive, chiefly because buried laccoliths and sills may have to be drilled through to reach the reservoir rock. If traps were formed around the ancestral high and then tilted as a result of the doming, the traps and their contents could have shifted and then been covered by laccoliths. Similarly oil and gas pools formed against the stocks could also be overlain by one or more laccoliths. The presence or absence of a laccolith in the path of a test well may well mean the difference between a test well which reaches the possible reservoir rock and one which does not. The porphyry body penetrated by the J. G. Dyer Drilling Co.'s Government 1 test well is probably a buried laccolith extruded southward from the West Mountain stock. The chance that a test well will penetrate one or more buried laccoliths increases nearer the stocks.

GOLD AND SILVER DEPOSITS

None of the gold and silver mines in the Abajo Mountains area—or the "Blue Mountain district" as it was once called—have been worked since 1943. Almost all the mine portals have caved in, and most of the mines are no longer accessible. Available records indicate that the deposits were all small and that none produced enough mineralized rock to repay the costs of driving the drifts or constructing the mills.

The details of the early exploration of this general region are given by Gregory [4] (1938, p. 108–110) in his discussion of the San Juan Country. Prospecting in the Abajo Mountains began about 1890, and by the turn of the century most of the prospectors had left, realizing that the gold and silver deposits in the area were small and insignificant.

The deposits were of two types—placer and lode. The placer deposits were restricted to Recapture and Johnson Creeks and produced only minor amounts of gold and silver. The lode deposits can be divided into those in and adjacent to the East Mountain stock, those adjacent to the West Mountain stock, and those near the margins of laccoliths.

In general, all the lode deposits, whether in a stock or at the margin of a laccolith, exhibit the same sulfides. Pyrite is the most common, and is widespread; little else is apparent. Chalcopyrite, sphalerite, and galena are present in minute quantities and commonly show only in polished sections of the rock. No gold was recognized, and apparently its tenor is low. Some records indicate it is present in amounts of less than 1 fine ounce per 1 short ton of ore. In a few specimens examined microscopically, thin minute seams of what may be ruby silver impregnated several fractures. The silver content of the ore is minute, about 1 ounce for every 5 tons of ore.

LODE DEPOSITS IN EAST MOUNTAIN STOCK

Much of the East Mountain stock is cut by closely spaced fractures that are filled chiefly with mosaic quartz (p. 47–49). The individual fractures range in width from about 0.02 to 1.7 mm; most are about 0.1 mm in width. They curve slightly, coalesce, and generally form a braided network. Each fracture is separated from its neighbor by segments of the host rock that are about 0.4 mm wide, although locally the segments are as much as 3.0 mm wide.

[4] After Thorpe, M. R., 1916, The Geology of the Abajo Mountains, San Juan County, Utah: Yale Univ., unpublished Ph.D. thesis.

Pyrite is common in the rock adjacent to the fractures, but is relatively uncommon in the quartz-filled fractures. Much of the pyrite has been altered to limonite, and this alteration accentuates the yellowish-orange appearance of the altered zone. Chalcopyrite, galena, and sphalerite are present in minor amounts; neither gold nor silver was noted in the specimens studied.

All the mines and prospects in the East Mountain stock have been dug in the fracture zone. The mine portals are now closed, but the headings suggest that most of the drifts followed the fractures.

Only three mines can be identified: the Gold Queen mine in the SE¼ sec. 11, T. 34 S., R. 22 E. (unsurveyed), the Danish Girl mine, which is about 300 feet east of the Gold Queen mine, and the Blue Bird mine in the NW¼ sec. 13, T. 34 S., R. 22 E. (unsurveyed; pl. 1).

The Gold Queen mine has been described by Gregory (1938, p. 109) as follows (details of location as cited contain minor inconsistencies):

> The Gold Queen mine, at the head of Gold Queen Gulch, southeast of Abajo Peak was once the scene of considerable activity. The discovery of a small vein of rich ore led to the construction of two tunnels, three shafts, cabins for miners, and a mill, at a reported cost of about $80,000.00. The mine is located on a mineralized zone about 600 feet wide that crosses the crest of a ridge. The igneous rock in this contact zone is filled with minute veins of iron ore, a little copper ore, and calcite. Extensive exploration by Carlson, Olsen, and Innis proved that the ore-bearing veins were tiny and the gold in them superficial. Operations were suspended about 1903.

In 1923, the Gold Queen mine was reopened, and a small amount of gold was recovered. Shortly after this, the mine was abandoned, the mill was dismantled, and its five stamps were moved to the Dream mill near the Dream mine (p. 102). Since then the aerial tramway that once served the mill has been dismantled and no trace of the mill remains.

Data are not available concerning either the Danish Girl or the Blue Bird mines; both of these are in the fractured zone.

LODE DEPOSITS NEAR WEST MOUNTAIN STOCK

Only a few prospects have been dug in the West Mountain stock, and the only mine—the Duckett mine—is near the east edge of the shatter zone that surrounds the stock.

Although the West Mountain stock is cut by fractures, these are neither as profuse nor as widespread as those that cut the East Mountain stock. All the prospecting has been in the fractured areas.

The Duckett mine, in the NE¼ sec. 18, T. 34 S., R. 22 E. (unsurveyed), consists of a shaft (now caved) and a drift about 35 feet long that follows the contact between the porphyry and the Mancos Shale. The contact trends about N. 80° W. and dips about 65° N. The igneous rock near the contact is cut by small fractures filled with limonite(?) and calcite which parallel the contact in strike and dip. Small amounts of pyrite are found along the contact. Gregory (1938, p. 109) reported that the mine, owned by J. A. and J. B. Duckett, produced only "* * * a few dollars per ton."

LODE DEPOSITS AT THE MARGINS OF LACCOLITHS

Some mineralized exposures are distant from the stocks and have formed at or near the margins of the laccoliths. Mines and prospects have been dug at some of these mineralized localities but only the Dream, Dixon's, Viking, and Alma mines, and the Log Cabin claim can be identified.

DREAM MINE

The Dream mine, in the SE¼ sec. 15, T. 34 S., R. 22 E. (unsurveyed), has been described by Gregory (1938, p. 109–110):

> The Dream mine, a group of seven claims at the head of Johnson Creek, was located by C. A. Cooley and S. J. Houser in 1893. After working the mine intermittently for 6 or 8 years, Cooley leased his interest to C. W. Houser, who is said to have taken out and sent to the mill $3,000 in gold. While the Housers controlled the property, Capt. Calvin Jackson, of Colorado, leased the Dream mine from them and founded Camp Jackson, where he built the first stamp mill in the mountains. His violent death soon after the mill was constructed ended the 'Camp Jackson boom.' Then the Housers failed and the Dream mine changed hands several times until it came into the charge of A. P. Adams, who built roads, and a stamp mill at a cost of about $35,000. After this Hansen and Young expended about $20,000, only to fail after extracting a small amount of gold. The Alamo Mining Co. next came into possession of the property, spent several thousand dollars in working it, then failed, and sold out to the present owners, S. J. and C. W. Houser. The mine workings consist of more than 2,000 feet of tunnels and crosscuts on three levels, two shafts, and a stamp mill. The tunnels are designed to penetrate the mineralized zone at the contact of the laccolith and its roof. The most valuable ore is near the surface. The gold is confined to the bedding planes of the metamorphosed sedimentary rocks and to a thin zone of igneous rock. All the ore is free-milling. Most of it has the form of fine flakes, but nuggets as large as nail heads have been found. A small amount of copper is present but not enough to prevent the use of cyanide. At the end of the largest tunnel the gold ore is a conglomerate of fragments of porphyry and argillite with much iron pyrite that has a reported value of $1 to $27 a ton. In one of the crosscut tunnels gold has been found in a breccia composed of fragments of Dakota(?) sandstone, Morrison shale, and blue porphyry. In another tunnel a band of sulphide ore was encountered. According to the owners 50 tons of rich ore is stored in the mine, 3,000 tons is on the dump, and 6,000 tons is in sight in the underground workings. S. J. Houser, who as owner or operator has been connected with the property since its discovery in 1893, states that the large sums spent on the development of the Dream mine and the nearby Goodhope and Puzzle workings have yielded returns.

Most of the workings are along the northwest flank of the anticline that is underlain by the Camp Jackson laccolith. In 1922 the late Walter C. Lyman became convinced that the ore found near the igneous body was only a minor showing and that much richer deposits were to be found in the porphyry at depth. He considered the igneous body to be a single dike of porphyry that had been intruded vertically from the parent magma. In an attempt to demonstrate the dikelike character of the intrusion, he dug a tunnel about 100 feet below most of the established workings. According to his son, Marvin F. Lyman of Blanding, Utah, the dike was intersected by this tunnel and small amounts of ore were recovered. Shortly thereafter, Lyman decided to dig another tunnel to intersect the dike at depth, where presumably richer ore would be found. Lyman, therefore, began the tunnel about 500 feet below the established workings. The portal of this tunnel, now partly concealed by debris, is exposed in the SE¼ sec. 15, T. 34 S., R. 22 E. (unsurveyed), near the point where Cooley Gulch is crossed by the Blue Mountain-North Creek road (pl. 1). This tunnel, known as the Marvin tunnel, is about 900 feet long and is almost entirely in sedimentary strata. Only small amounts of ore were found, according to Marvin Lyman.

At the time Lyman began the Marvin tunnel, he and F. J. Adams also started to rebuild and modernize the mill near the Dream mine. The five stamps and other equipment removed from the Gold Queen mill were transported laboriously to the Dream mill. When the rebuilding was finished, the Dream mill consisted of ten stamps and was equipped to recover bullion by amalgamation and cyanidation.

After Lyman failed to find significant deposits of ore in the Marvin tunnel, he moved back to the original workings. During 1924, he mined a small quantity of gold that was recovered in the newly built mill. In all, the mill was operated intermittently for about a month before it was closed. In 1958 only the framework of the mill stood and most of the equipment had been removed.

Lyman continued to work around the Dream mine until his death in 1943, but no ore was produced. The Dream mine was the last to be operated in the Blue Mountain district.

Marvin F. Lyman reported that most of the gold found was free gold in the upper part of an igneous dike. All the mine workings penetrated a thin layer of Morrison strata, and then followed the contact between the porphyry and the surrounding rocks.

Samples of the rock mined were collected from an old ore bin. Pyrite is the most common sulfide, and dominates the assemblage. Other sulfides found in very small amounts include chalcopyrite, galena, and sphalerite. A few thin veinlets of what may be ruby silver were noted, but the amounts are too small for positive identification. Limonite pseudomorphs after pyrite are common.

DIXON'S MINE

Dixon's mine is near the floor of Cooley Gulch in the center of the W½ sec. 14, T. 34 S., R. 22 E. (unsurveyed), about 3,000 feet northeast of the Dream mine. The workings consist of a small drift that follows the contact of Morrison strata with an igneous body. Only a small segment of the igneous body is exposed along the floor of Johnson Creek, but it is tentatively interpreted as part of a laccolith. The strata overlying the igneous body are conformable, and near the south edge of the exposure they strike about N. 14° W., and dip about 9° SW. The mine workings are in this locality and follow a zone marked by a concentration of pyrite. As far as is known, no ore was produced and no ore minerals were recognized in the dump.

VIKING MINE

The Viking mine, near the center of sec. 14, T. 34 S., R. 22 E. (unsurveyed), is on the crest of the concealed Camp Jackson laccolith, adjacent to one of the small faults in strata west of the East Mountain stock. Gregory (1938, p. 109) described the mine as follows:

> * * * The Viking mine, located by James Hewett and Henry Rose on the ridge northeast of the Dream mine, was developed by sinking two shafts and driving a tunnel 400 feet long into the mountain at the contact between the porphyry and Dakota(?) sandstone. No valuable ore was found.

LOG CABIN CLAIM

Several small piles of tailings about 700 feet east of the Viking mine may represent the Log Cabin claim mentioned by Gregory (1938, p. 109):

> Just east of the Viking mine the owners of that property staked out the Log Cabin claim and sunk a shaft and a tunnel into decomposed igneous rock near its upper contact. Small fissures in this rock are filled with iron ore and calcite associated with gold in amounts too small for profitable mining.

This mine also seems to be near the roof of the concealed Camp Jackson laccolith. It is reported that gas in the shaft caused work on the property to be discontinued.

ALMA MINE

The Alma mine is in the SE¼ sec. 23, T. 34 S., R. 22 E. (unsurveyed), along the southeast flank of the Arrowhead laccolith. Gregory (1938, p. 109) reported:

> In an effort to relocate the old "Spanish mine," said to have been worked "300 years ago before it was buried in a landslide," Andrew Straus located the Alma mine at the south base of South Peak, in 1900 and, taking into partnership William Straus and S. J. Houser, worked the property for some years. Several tunnels driven into a mineralized zone in the porphyry yielded no valuable minerals, but a small amount of free gold was found nearby on Recapture Creek. That some gold-bearing ore was shipped from this vicinity is shown by records at Santa Fe.

The portals of both tunnels are now caved in, and the area is covered with a dense growth of aspen. The tailings show only small amounts of pyrite; no ore minerals were recognized.

COPPER DEPOSITS

Mines at two localities in the Abajo Mountains are reported to have produced copper ore: the Copper Queen and the Tuffy Copper. Neither of the mines is believed to have produced significant amounts of copper. Of the two, the Copper Queen mine is larger and has more copper minerals exposed.

COPPER QUEEN MINE

The Copper Queen mine, in the SE¼ sec. 35, T. 33 S., R. 22 E. (unsurveyed), along the west wall of North Creek, consists of several small drifts in Dakota and Burro Canyon strata. Gregory (1938, p. 107) described the mine as follows:

> * * * The Copper Queen mine, in North Canyon, has been developed by the construction of two tunnels, three shafts, and an open cut. From one of the shafts a lenticular mass of malachite 2 feet wide is said to have yielded $14 a ton. The ore is in Dakota(?) sandstone, here quartzitic, and is concentrated in a zone of fractures.

In this locality the Dakota and Burro Canyon are overlain by a thin layer of Mancos Shale and underlain by the east flank of the Horsehead laccolith. The sedimentary strata strike about N. 10° E., and dip about 53° NW. Both the Dakota and Burro Canyon and the Mancos Shale are cut by fractures that are presumably the result of the intrusion of the Horsehead laccolith. Azurite and malachite are widespread, and locally pyrite and chalcopyrite impregnate both units. Other copper minerals noted include small quantities of chalcocite, bornite, covellite, and chrysocolla.

The copper minerals are mostly in the Dakota and Burro Canyon. The minerals coat bedding and cross-bedding planes, and fill the minute fractures in the sandstone. The tunnels follow the strike of the beds, and have been dug along what appear to be the zones of greatest copper concentration.

TUFFY COPPER MINE

Some details of the Tuffy Copper mine were described in the section on uranium-vanadium deposits (p. 86–87), and little additional description is needed here (fig. 38).

The copper minerals are disseminated along the crossbedding planes of the Entrada Sandstone. They coat the sandstone laminae and form a zone 1 to 2 feet thick that can be traced as a nearly horizontal band both in the mine and along the outcrop. In detail, the zone can be divided into two unequal parts: (a) a basal part about 2 inches thick marked by a concentration of dark-gray (N3) to black (N1) specks in the sandstone and (b) an upper part 12 to 24 inches thick that contains many small nodules, ¼ to ½ inch in diameter, of secondary copper minerals disseminated through the sandstone. Azurite and malachite make up the dominant part of these small nodules. Locally the centers of these nodules contain dark-gray to black specks similar to those in the basal part of the zone. This dark center is encircled by a thin band of azurite, which in turn is surrounded by a band of malachite.

A sample including a segment of both parts of the zone was identified by A. G. King (written communication, 1955). His report states in part:

> The ore minerals are very fine grained and interstitial between the sand grains. Because of the particle size, the ore minerals were not identified in polished section. Heavy liquid separations failed to isolate the ore minerals. Some of the fine interstitial material is strongly anisotropic and is probably a manganese oxide. The copper is contained in malachite and possibly a sulfide which was not identified.

Although the black material cannot be identified, its position in the center of nodules composed chiefly of such secondary copper minerals as azurite and malachite suggests that it may be finely disseminated chalcocite containing minor amounts of carbonaceous matter.

WATER RESOURCES

Water probably is the most important natural resource of the Abajo Mountains area, and the existence of two communities, Monticello on the east and Blanding on the south, depends upon a steady uninterrupted supply.

Much of the water used by the towns and by the neighboring farms is from spring-fed streams that head in the mountains. Most of these streams are perennial although, at a distance from the mountains, the water in some of them sinks into the alluvium to continue downslope as ground water. Melting snow increases the runoff during April, May, and June (table 12). As a result, severe spring floods are common and much water is lost that might otherwise be used during the dry summer months.

As the populations of the cities of Monticello and Blanding have grown, the need for adequate supplies of potable water has increased markedly. Blanding has solved the problem, at least temporarily, by ingenious diversion tunnels and pipelines. Monticello has attempted to solve the problem by tapping new stream sources.

SURFACE WATER

The streams that debouch from the north flank of the mountains are used chiefly for watering livestock. One or two small farms use some water for irrigation, but most of the water flows northward to empty eventually into the Colorado River. The headwaters of one of the streams that empties into Harts Draw are diverted by a small irrigation ditch into the drainage of the eastward-flowing Spring Creek (SW¼ sec. 14, T. 33 S., R. 22 E.). Indian Creek, which also flows northward, has had part of its flow diverted southward for use by Blanding (p. 104–105).

The streams that drain the east flank of the mountains are used extensively. Spring and South Creeks are used for irrigation and also for livestock. North, Bankhead, and Pole Creeks are the main sources of water for Monticello. Small inlet ducts have been placed near the heads of these creeks and the water is carried by pipeline to two settling reservoirs on the western outskirts of Monticello. As of 1957, the water was not treated and, to insure that it would not be contaminated, the watersheds at the heads of these streams were closed to camping, recreation, and stock grazing. In the spring of 1958, plans were under way to secure additional water for Monticello by tapping both South Creek and the stream in Gold Queen Gulch. When pipelines from these streams are completed, Monticello will secure water from five sources: North Creek, Bankhead Creek, Pole Creek, South Creek, and the stream in Gold Queen Gulch.

Those streams along the southeast flank of the mountains—Dickson Creek and the streams in Long, Devil, and Bulldog Canyons—are used chiefly for irrigation and livestock.

Several of the streams that drain the south flanks of the mountains supply Blanding with water. Johnson Creek is the principal source, although water from several other streams adds to its flow. Chief among these is Indian Creek, part of whose flow has been diverted into a tunnel which passes through Jackson Ridge. The tunnel is below the toe of the

Camp Jackson laccolith and is almost entirely in sedimentary strata. A porphyry sill, about 6 feet thick dipping southward, is about 200 feet from the south entrance of the tunnel; it is the only igneous rock exposed in the tunnel. A small pocket of sulfide minerals localized in eastward-trending fractures was found about 2,600 feet north of the south entrance. Pyrite, galena, and sphalerite made up most of the sample, and minute amounts of gold and silver are reported to have been found.

The entrance to the tunnel is in the center of the N½ sec. 9, T. 34 S., R. 22 E. (unsurveyed), near the Indian Creek Ranger Station. From that point the tunnel extends in a straight line for about 1 mile along a trend of about S. 15° E. to its exit in the NE¼ sec. 16, T. 34 S., R. 22 E. (unsurveyed). The waters here join a small tributary of Johnson Creek.

Part of Recapture Creek is also diverted into the Johnson Creek drainage. Here, however, the waters near the head of Recapture Creek enter a pipeline that crosses a high ridge and empties into the Camp Jackson reservoir. This reservoir occupies the site of the old Camp Jackson mining community and is in the NW¼ sec. 23, T. 34 S., R. 22 E. (unsurveyed). The waters from the reservoir are then fed into Johnson Creek.

Blanding is supplied, therefore, by water from three distinct and separate sources: Johnson Creek, Indian Creek, and Recapture Creek. The waters flow southward in Johnson Creek and enter an intake in the NW¼ sec. 28, T. 34 S., R. 22 E. (unsurveyed), near a point where the Blue Mountain-North Creek road crosses Johnson Creek. From the intake, the water is carried by pipeline to a settling reservoir near Blanding. The water is not treated, and consequently the watersheds of Johnson, Indian, and Recapture Creeks are closed to camping, recreation, and the grazing of livestock.

The streams that drain the southwest flank of the mountains are used chiefly for livestock and to a lesser

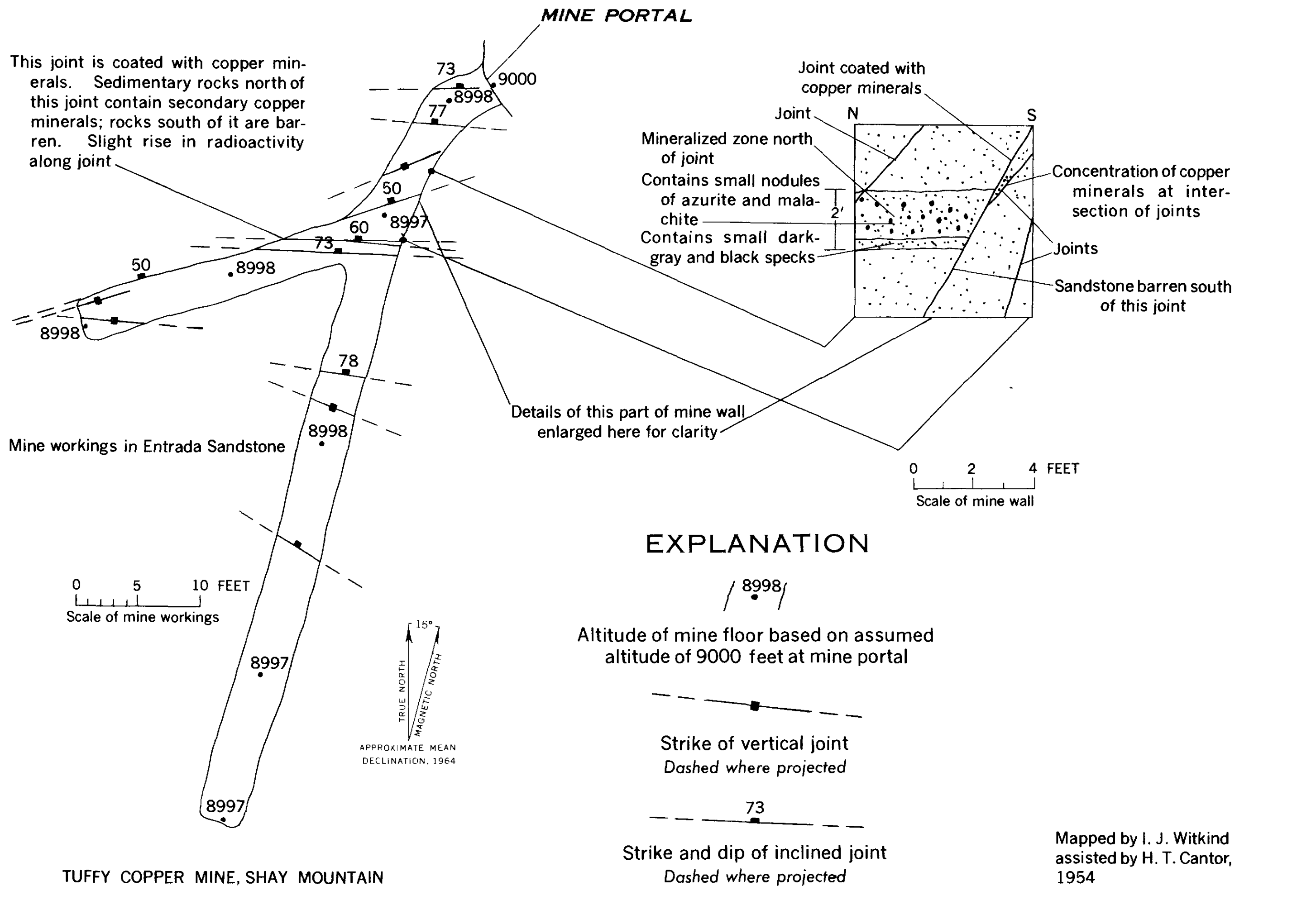


FIGURE 38.—Workings of the Tuffy Copper mine.

TABLE 12.—*Monthly and yearly discharge of Indian Creek as measured at two gaging stations in the Abajo Mountains area*

[Data compiled from U.S. Geological Survey Water-Supply Papers 1213, 1243, 1283, 1313, 1343, and 1393]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Mean or total
A. GAGING STATION IN THE SW¼ SEC. 4, T. 34 S, R. 22 E. (UNSURVEYED)													
In second-feet													*Mean*
1950	2.0	1.75	1.16	1.0	1.5	2.0	6.89	10.4	9.36	2.57	1.08	0.78	3.37
1951	.55	.33	.35	.3	.3	.35	.97	4.78	4.68	1.30	.91	1.19	1.33
1952	.82	.57	.40	.30	.30	.50	5.95	45.1	26.5	3.95	1.21	.42	7.16
1953	.31	.20	.2	.2	.2	.26	2.24	5.34	5.00	.83	.47	.23	1.29
1954	.20	.14	.1	.1	.1	.2	3.93	10.8	1.97	.47	.20	.44	1.55
1955	.77	.23	.22	.1	.1	.2	5.99	15.6	6.38	1.15	2.54	.40	2.81
In acre-feet													*Total*
1950	123	104	71	61	83	123	410	638	557	158	67	46	2,441
1951	34	20	22	18	17	22	58	294	278	80	56	71	970
1952	50	34	25	18	17	31	354	2,770	1,580	243	74	25	5,221
1953	19	12	12	12	11	16	133	328	298	51	29	14	935
1954	12	8.5	6.1	6.1	5.6	12	234	663	117	29	12	26	1,131.3
1955	47	14	14	6.1	5.6	12	356	957	379	71	156	24	2,041.7
B. GAGING STATION IN THE SW¼ SEC. 21, T. 32 S., R. 22 E.													
In second-feet													*Mean*
1950	4.33	3.52	2.26	1.80	2.42	3.28	11.4	17.5	15.8	4.03	1.19	1.52	5.76
1951	1.34	1.35	1.16	.92	.80	.89	1.77	6.88	5.87	1.15	1.53	1.46	2.09
1952	1.20	.93	.76	.89	.97	1.16	18.6	64.5	39.5	7.19	3.06	1.15	11.65
1953	1.29	1.39	1.03	1.08	1.19	1.08	3.59	7.73	7.79	1.14	1.20	.47	2.42
1954	.87	1.09	.98	.45	.36	.72	5.52	15.8	4.38	.97	.45	1.78	2.78
1955	1.41	1.13	1.02	.9	.9	1.77	6.72	24.0	12.9	2.44	3.39	.62	4.77
In acre-feet													*Total*
1950	266	209	139	111	135	202	680	1,080	939	248	73	90	4,170
1951	83	81	71	57	44	55	106	423	349	71	94	87	1,521
1952	74	55	47	55	56	71	1,100	3,970	2,350	442	188	68	8,476
1953	80	83	63	66	66	67	214	475	464	70	74	28	1,750
1954	54	65	60	27	20	44	328	973	261	60	28	106	2,026
1955	87	67	63	55	50	109	400	1,480	770	150	208	37	3,476

extent for the irrigation of several small farms along the stream courses. These streams empty eventually into the San Juan River.

GROUND WATER

Little has been done to develop the ground-water resources of the area, chiefly because adequate supplies of potable water cannot be found at a shallow depth. The major problem that plagues the nearby communities is the lack of facilities for gathering and storing the runoff. Unable to finance a dam near Monticello, the inhabitants have underwritten the drilling of at least one well in the western outskirts of the town in a search for ground water. The well was drilled to a depth of about 540 feet, and it is reported to have penetrated the Dakota and Burro Canyon without finding water. This failure of the Dakota and Burro Canyon to yield water is puzzling for nine wells at the uranium-vanadium mill in Monticello struck water in this unit. The water, however, is reported to be so strongly mineralized that the wells are not used by the mill, which secures the needed water from the Monticello water supply. Each of the wells has a pumping capacity of about 30 gallons a minute. Another well, the Hall well about 1 mile east of the mill, was drilled to a depth of about 1,050 feet—the base of the Navajo Sandstone. Potable water was found at this horizon. The well produces from both the Dakota and Burro Canyon and the Navajo Sandstone. If both units are tapped, the well is capable of producing about 120 gallons of water a minute. The well penetrated the Entrada Sandstone but did not find water in that unit. It appears, therefore, that only the sandstones in the Dakota, Burro Canyon, and Navajo are suitable near-surface aquifers and, of these, water from the Dakota and Burro Canyon is unfit for human consumption.

Springs are numerous and most of them are around the margins of the large boulder fields. Several road cuts across these boulder fields have disclosed that detritus near the base of the field is tightly cemented by ice. Presumably the ice, protected by the overlying boulders, melts gradually during the summer months and supplies a constant source of water to feed the springs. Each fall and winter the ice is replenished.

The springs flow most abundantly during the early summer months. As the dry weather sets in, many of the smaller springs dry up; others, however, continue to flow and these have become well known. Cold Springs, in the NE¼ sec. 26, T. 34 S., R. 22 E. (unsurveyed), near the south flank of the South Peak laccolith is used annually by sheepherders who make their camp nearby. A large excellent spring in the SE¼ sec. 28, T. 34 S., R. 22 E. (unsurveyed), once supported a community known as Springfield, most of whose residents were miners in the Camp Jackson area. This spring flows from a disintegrated porphyry mass tentatively interpreted as either part of a dissected sill or part of the floor of a dissected laccolith.

Many springs flow from the base of the sandstone aquifers that crop out in valley walls. These springs supply most of the water to North Cottonwood Creek and to the stream in Tuerto Canyon. Both small and large springs are along the trace of the South Shay fault where it cuts sandstone aquifers.

In general, the dense vegetation in many of the valleys indicates the widespread nature and adequacy of the springs.

The water from all the springs is potable, of excellent quality, cold and clear.

ROAD METAL

The pediment deposits that encircle the mountains on the north, east, and south are suitable sources of road metal. Both the State and county highway departments have opened pits in these deposits and use the rock extensively. Generally the material has to be crushed, sized, and washed before it can be used.

The considerable amount of included chert and other varieties of cryptocrystalline quartz in the deposits suggests that the gravel will react with high-alkali cement if it is used for any large-scale construction purposes.

RIPRAP

The boulder fields of porphyry are an excellent source of riprap, which is used for facing earth dams, and, if it were crushed and sized, could be used for road metal. The boulders are as much as 4 feet long by 3 feet wide by 1 foot thick, and are easily accessible on any one of several roads into the mountains (pl. 1). Any one of the boulder fields along the mountain flanks will furnish large quantities of riprap.

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