# Geology and Uranium-Vanadium Deposits of the La Sal Quadrangle San Juan County, Utah, and Montrose County, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 508

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

# Geology and Uranium-Vanadium Deposits of the La Sal Quadrangle San Juan County, Utah, and Montrose County, Colorado

*By* WILLIAM D. CARTER *and* JAMES L. GUALTIERI

GEOLOGICAL SURVEY PROFESSIONAL PAPER 508

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

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. GS 65-325

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

# CONTENTS

# ILLUSTRATIONS

[Plates are in pocket]

# TABLES

# GEOLOGY AND URANIUM-VANADIUM DEPOSITS OF THE LA SAL QUADRANGLE, SAN JUAN COUNTY, UTAH, AND MONTROSE COUNTY, COLORADO

By William D. Carter and James L. Gualtieri


## ABSTRACT

During the period from 1952 through 1956 the U.S. Geological Survey conducted exploration by diamond drilling for uranium-vanadium deposits in the Salt Wash Member of the Morrison Formation of Jurassic age in the La Sal Creek area, and mapped the geology of the surrounding La Sal (15 minute) quadrangle, Utah-Colorado.

The La Sal quadrangle, comprising about 240 square miles of San Juan County, Utah, and Montrose County, Colo., is in the Canyon Lands section of the Colorado Plateau. Upper Paleozoic, Mesozoic, and Cenozoic sedimentary rocks cover most of the area. These are gently folded and faulted by uplift, intrusion, and collapse of plastic evaporite masses on the east and by intrusion of laccolithic complexes now composing the La Sal Mountains on the west. The folding of the salt anticlines occurred at different times. The latest folding of the anticlines, accompanied by igneous intrusion, took place during the Late Cretaceous and early Tertiary periods and may have extended through Miocene time. Certain laccolithic bodies may have intruded the sedimentary rocks higher in the stratigraphic column prior to emplacement along lower stratigraphic horizons.

Exploration by the U.S. Geological Survey resulted in the discovery of 115,000 tons of uranium-vanadium ore in a mineral-rich belt that trends N. 70° E., is approximately 6 miles long, and ranges from 500 to 3,000 feet in width. Almost all the ore is in the uppermost continuous sandstone of the Salt Wash Member of the Morrison Formation. The strata of the ore-bearing sandstone range in thickness from a few feet to 105 feet. The strata are medium-to fine-grained quartzose sandstone interbedded with siltstone and mudstone. Near the uranium-vanadium deposits the sandstone is white, light gray, or light brown, and the siltstone and mudstone are usually light green or gray green. Away from the deposits the sandstone and mudstone units are shades of reddish brown.

In the area of La Sal Creek Canyon the lower beds of the ore-bearing sandstone fill a northeast-trending paleostream channel containing local scours that are as much as 20 feet deep. The scours are filled by sandstone in which cross-stratification, current lineation, ripple marks, mud cracks, and slumping and compaction structures are common. These structures have been recognized in the mines and help to determine the direction of stream flow during deposition of the Salt Wash. The main channel in the La Sal Creek area has been defined by exploratory drilling and found to coincide with the area that is considered favorable for the presence of uranium-vanadium deposits.

Uranium and vanadium minerals occur together as bedded or roll deposits impregnating sandstone and siltstone and as replacement bodies in accumulations of carbonaceous and mudstone debris. The ore bodies, although extremely irregular in size and shape, are elongate, usually have sharp boundaries, and are oriented en echelon roughly parallel to the trend of sedimentary structures. Individual bodies may contain from a few pounds to several thousand tons of ore-grade material. These bodies are clustered in such a manner that several thousand tons can be removed from a single mine.

Uranium minerals in the area include uraninite and uranyl silicates, phosphates, arsenates, and vanadates. Vanadium is closely associated with the uranium as silicates, vanadates, and oxides. Individual deposits are either dominantly unoxidized or oxidized. The unoxidized ores contain minor amounts of sulfides, arsenides and selenides. The ratio of vanadium to uranium averages 6 : 1 and ranges from 4 : 1 to 14 : 1, reflecting the gross mineral composition of the deposits.

The localization of uranium and vanadium minerals in sandstone probably was controlled by (1) the position of the sandstone beds in the channel, (2) the presence of mudstone films, seams, and mudstone-pebble conglomerate beds which affects the permeability of the sandstone lenses, and (3) the presence of carbonized wood and plant remains within the beds. Folds, faults, and fractures have no apparent relation to the localization of the uranium-vanadium deposits. Secondary ore minerals, however, fill fractures as a result of recent oxidation and ground-water movement.

Exploration guides that have been used successfully in the La Sal Creek area to locate uranium-vanadium ore bodies are as follows:

1. White, light-brown, or light-gray, lenticular sandstone, 30 feet or more in thickness, underlain by, interbedded with, and (or) overlain by gray, gray-green or light-green mudstone.
2. Irregularities at the base of the ore-bearing sandstone: channels, bar and swale topography, and cuspate or noselike projections along the channel margins.
3. Trash pockets: accumulations of mudstone pebbles and carbonaceous debris.


## INTRODUCTION

The La Sal quadrangle (fig. 1) includes about 240 square miles along the Utah-Colorado boundary in the Canyon Lands section of the Colorado Plateau (Fenneman, 1931, p. 306–312) between long 109°00′ and 109°15′ and lat 38°15′ and 38°30′. The area is in the northeast corner of San Juan County, Utah, and in the

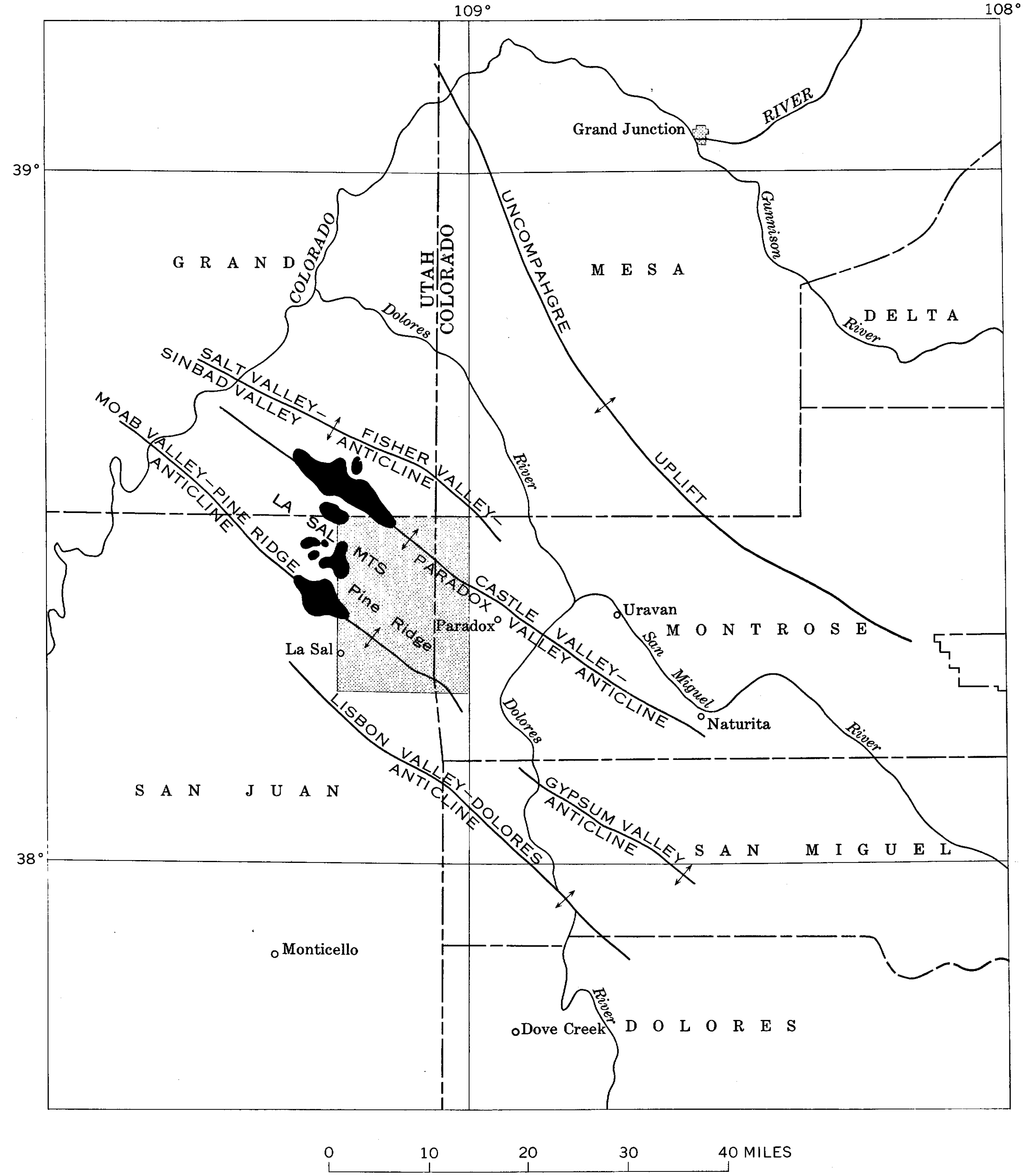



**Figure 1.—Location of the La Sal quadrangle and major structural features of the esatern part of the Colorado Plateau.**

northwest corner of Montrose County, Colo.; more than half of the area is in the Manti-La Sal National Forest.

The area is sparsely populated. The small village of La Sal, Utah, near the southwestern margin of the area has a general store and post office to accommodate the inhabitants of the surrounding countryside.

Access to the area is by Utah Highway 46, an all-weather paved road which connects with U.S. Highway 160 at La Sal Junction, to the west, and Colorado Highway 90 at the Utah-Colorado line in La Sal Creek Canyon. Colorado Highway 90 extends from the mapped area eastward through Paradox and Bedrock, Colo., to Naturita where it connects with Colorado Highway 140. An intricate network of Forest Service roads, drilling access roads, and jeep trails makes most of the area accessible during the dry months of the year. Three small landing strips for light aircraft are available in the southern half of the area.

*Previous work.*—Many geologists have visited the mapped area since A. C. Peale (1877a, b) made a short visit in 1875. Geologic work and reports specifically dealing with the area, however, have been limited to early reconnaissance studies of the uranium-vanadium deposits made by Coffin (1921) and a preliminary study of the igneous rocks of the La Sal Mountains by Gould (1926). Additional economic studies were made by Fischer (1942). Detailed studies of the uranium-vanadium deposits were made by C. W. Livingston (written commun., 1945) for the Manhattan Project. In 1952 the igneous rocks of the La Sal Mountains were studied in detail by Hunt and A. C. Waters (Hunt, 1958). At the same time, Richmond (1962) studied the glaciology and the surficial deposits of the La Sal Mountains area.

*Purpose and scope of report.*—This report describes the geology and uranium-vanadium deposits of the La Sal quadrangle. The fieldwork was undertaken by the U.S. Geological Survey on behalf of the Raw Materials Division of the U.S. Atomic Energy Commission as part of a program to stimulate the search for and mining of uranium in the Colorado Plateau. The investigations were initiated to help develop known deposits, to explore for new deposits, and to search for new areas containing uranium-vanadium deposits. They also provided data on the regional geology of the area and thereby aided in the evaluation of the uranium resources of the Colorado Plateau.

*Fieldwork.*—An exploration drilling program was started in May 1952 under the direction of George K. Brasher and Richard C. Douglas. From April 1953 to November 1956 the drilling was supervised by the authors. During 1953 D. C. Hedlund and R. C. Doman acted as geologic assistants. J. C. Warman and W. R. Barton joined the party in 1954 and 1955, respectively and worked as geologic assistants until the fall of 1955. During the drilling program the field party was supplemented by a sampler foreman, Glen Kralicek, and several samplers who had continual supervision of the drill rigs and handled the core samples.

Diamond drilling on close-spaced centers (holes 50–100 ft apart) behind mine faces of the Evening Star, Gray Daun, and Vanadium Queen mines discovered new ore bodies and led the Survey to enlarge its program to widespread subsurface exploration. A total of 505 diamond-drill holes totaling 123,371 feet were completed in the La Sal Creek area during the seasonable months of 1952, 1953, and 1954. The winter months of 1953 through 1955 were devoted to subsurface mine studies to determine the size, configuration, ore controls, and mineralogy of the ore bodies and to discover guides which might aid the search for new areas favorable for the occurrence of uranium-vanadium deposits. By the end of 1954, private industry showed sufficient active interest in the search for uranium that the U.S. Geological Survey party withdrew from physical exploration and devoted full time to geological investigations. These investigations began late in the spring of 1954 and were carried on concurrently with the final drilling program which terminated late in 1954. Field investigations and map compilation continued and consisted of mapping the geology of the La Sal quadrangle and detailed studies of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. The mapping and related studies were completed in November 1956.

Most of the mines in the La Sal Creek area were mapped by tape and compass methods on a scale of 1 inch equals 20 feet. Maps of the drilling area were made by transit surveys on a scale of 1 inch equals 1,000 feet. Areal geologic mapping was done by plotting the geology on aerial photographs, scale 1:37,500, and transferring it to topographic maps, scale 1:24,000, by means of photogrammetric plotters. This scale was subsequently reduced to 1:62,500 (pl. 1).

*Acknowledgments.*—The authors wish to express their gratitude to the Stocks-Gramlich Corp., The Vanadium Queen Mining Corp., U.S. Vanadium Corp., Four Corners Uranium Corp., and Vanadium Corp. of America for their cooperation in the exploration and mine-mapping phases of the project; to Messrs. H. S. Stocks, J. B. Crowley, A. M. Stocks, and W. Hall, residents in the La Sal Creek area, Messrs. J. W. Gramlich, Howard Balsley, and Abe Day of Moab, Utah, for information on the history and geography of the area, and to Mr. J. N. Plake, surveyor, who made the base maps of the area explored by diamond drilling. The authors wish to express their appreciation also to A. D. Weeks, M. E. Thompson, Theodore Botinelly, R. G. Coleman, L. R. Stieff, T. W. Stern, and Mona Frank of the Geological Survey who contributed information on the mineralogy of the deposits.

## GEOLOGIC SETTING

Exposed within the La Sal quadrangle, Utah-Colorado, is a sequence of Upper Paleozoic, Mesozoic, and Cenozoic sedimentary rocks (pl. 1) which have been uplifted by movement of plastic evaporite masses to form a series of three northwest-trending anticlines. A fourth anticline lies outside the mapped area. Between

777-039 O—65——2

these major anticlinal areas are three major synclinal folds. On the west the sedimentary rocks have been uplifted and intruded by three groups of laccolithic masses which form the La Sal Mountains. Many minor anticlinal and synclinal folds occur where the crests of the major anticlines were breached by erosion and where subsequent solution or flowage of salt led to the collapse of the overlying strata. Parts of such areas form large valleys.

The sedimentary formations are exposed in these valleys and nearby canyons and mesas, and in the hogbacks surrounding the igneous rocks. Thinning of beds, angular unconformities, and wedging out of entire formations indicate a history of periodic uplift of the evaporite masses. Faults and joints resulting from both uplift and collapse of the salt anticlines and from uplift by intrusive igneous bodies are common.

Most of the economic deposits of uranium and vanadium in sandstone are in the east-central part of the area; low-grade deposits of coal, copper, and iron are around and within the La Sal Mountains. Vein deposits of argentiferous copper have been exploited east of the area.

## STRATIGRAPHY

### GENERAL DESCRIPTION

Sedimentary rocks exposed within the La Sal quadrangle attain 8,500 feet or more in thickness and range in age from Pennsylvanian to Recent. The oldest rocks, the Hermosa Formation of Pennsylvanian age, crop out in the floor of Sinbad Valley in the northeast corner of the area and are probably in contact with the igneous rocks of the North and South Mountain groups of the La Sal Mountains. The next overlying formations, the Rico of Pennsylvanian and Permian age and the Cutler of Permian age, are exposed in the walls of Sinbad Valley and also around the igneous rocks of the North and South Mountain groups. These formations are poorly exposed in the mountainous areas and are, therefore, together with the Hermosa Formation, considered as a single mapping unit. Triassic and Jurassic formations crop out on the walls of Sinbad Valley and Roc Creek canyon and form the sharp hogback surrounding the North and South Mountain groups. In addition, the Jurassic formations are exposed in La Sal Creek Canyon, Sharp Canyon, at the northwest end of Paradox Valley, near Coyote Wash in the southeastern part of the area, and in the Middle Mountain group. High mesas capped by rocks of Early and Late Cretaceous age cover almost half of the area. The youngest sedimentary rocks, with the exception of Tertiary(?) fanglomerate and Recent gravel, are those of the Mancos Shale of Late Cretaceous age. These rocks are restricted almost entirely to the synclinal structures of Taylor Creek, Geyser Pass, and La Sal Pass. Consolidated gravel of Tertiary(?) age crops out along Geyser and Deep Creeks. Recent deposits of unconsolidated stream gravel and glacial and landslide debris flank the three uplifted igneous centers of the La Sal Mountains; deposits of windblown material and sheet wash are widely distributed on the mesas and valley floors. The stratigraphy of the area is summarized in the columnar section shown on plate 2.

### PENNSYLVANIAN SYSTEM

#### HERMOSA FORMATION

The Hermosa Formation of Pennsylvanian age crops out in the floor of Sinbad Valley in the northeast corner of the La Sal quadrangle and in the adjacent quadrangles to the north and east which cover Sinbad Valley, Roc Creek, and Paradox Valley. The Hermosa Formation is divided into two members: the lower, the Paradox Member, composed predominantly of salt and gypsum; the upper, an unnamed member, composed of limestone and red beds, including arkose.

The Paradox Member of the Hermosa Formation crops out in the floor of Sinbad Valley as isolated hillocks surrounded by alluvium. Because the beds—composed of gypsum, black shale, micaceous sandstone, arkose, limestone, and limestone breccia and conglomerate—are highly contorted, it is impossible to reconstruct the true stratigraphic sequence or to determine accurately the thicknesses. Wells drilled in Sinbad and Paradox Valleys indicate that, at depth, salt is the major constituent of the Paradox Member. One well in Paradox Valley, about 8 miles east of the La Sal quadrangle, was drilled through approximately 11,000 feet of the Paradox Member and did not penetrate the base. This great thickness is attributed to flowage of the salt during formation of the salt anticlines.

The upper member of the Hermosa Formation is exposed in an isolated belt along the southwest side of Sinbad Valley. The beds, dipping steeply to the southwest, are about 500 feet thick and are composed of gray arkose and some fossiliferous limestone. The Ayers well 1, located west of Bedrock, Colo., and 5 miles east of the La Sal quadrangle, was drilled on the southwest flank of the Paradox anticline. It penetrated 1,475 feet of gray and brown limestone interbedded with gray, green, and red arkosic sandstone lenses. The sandstone lenses are more abundant in the lower 285 feet of the well. The well was abandoned before it reached the Paradox Member. The upper member in the Rico area ranges from 1,800 to 2,000 feet in thickness (Cross, Spencer, and Purington, 1899). The member ranges from 1,500 to 1,800 feet in thickness in the Moab area (Baker, 1933, p. 19), is 1,300 feet thick in the Green River area (Baker, 1946), and is 600 feet thick on the San Rafael Swell (Baker, 1946); general thinning in a westerly direction is thus indicated. It is quite probable, therefore, that at least 1,800 feet of the upper limestone member of the Hermosa Formation underlies the La Sal quadrangle.

## PENNSYLVANIAN AND PERMIAN SYSTEMS

### RICO FORMATION

The Rico Formation, considered to be of Pennsylvanian and Permian age by the Geological Survey, may crop out close to the intrusive rocks of North and South Mountains of the La Sals. Doubt of its presence is expressed because much of the interval elsewhere occupied by the Rico is covered by landslide debris from the adjacent formations in the mountain area. Isolated exposures of white crystalline, dark-gray, and yellow-brown limestone crop out in a narrow belt surrounding the igneous rocks. Springs issuing from the limestone are quite salty; this feature was also noted by Baker (1933, p. 24) for the Rico Formation in the Moab district. No fossils were recognized in the limestone, but the dark-gray limestone gives off a petroliferous odor when broken. Numerous copper prospects, particularly those on the southwest flank of the North Mountain group, show that Rico limestone is in close proximity to the igneous rock.

The limestone is notably absent on the northeast flank of the Paradox Valley-North Mountain-Castle Valley anticline, in areas east and northwest of the quadrangle where, if present, it would certainly be exposed. This absence suggests that the limestone has been truncated by an unconformity at the base of the Cutler, by a post-Cutler unconformity, or by the igneous intrusion of North Mountain. The Ayers well 1, east of the mapped area near Bedrock, Colo., is on the southwest flank of the structure; it penetrated 630 feet of interbedded limestone, limy siltstone, and limy arkosic sandstone believed to represent the Rico Formation. Baker (1933, p. 23) describes the Rico as "a bedded series of sandstone with some red to lavender shale and several thin layers of limestone." He states that the upper limit is the top of the highest fossiliferous limestone, locally known as the "Shafer Limestone." Inasmuch as no fossils have yet been found in the limestone surrounding the igneous rocks of North and South Mountains, the age and formational designation of the limestone are uncertain. Conglomeratic sandstone beds typical of the overlying Cutler Formation, however, are stratigraphically higher than the limestone; therefore, the limestone is considered pre-Cutler and, although it could be assigned to the Hermosa Formation, it is herein referred to as Rico but mapped with the Cutler as one unit.

## PERMIAN SYSTEM

### CUTLER FORMATION

The Cutler Formation of Permian age is poorly exposed in most of the La Sal quadrangle. It is a sequence of white, pink, maroon, and purple conglomerate and arkose and red-brown sandy mudstone resting conformably on the Rico Formation in the Moab area (Baker, 1933, p. 29). In the Gateway area (Cater 1954b) the conglomerate and arkose beds contain "grains of fresh feldspar, and dark minerals, and pebbles and boulders of granite, gneiss, schist, and quartzite—material derived almost entirely from the Precambrian rocks that underlie the Uncompahgre Plateau."

The Cedar Mesa Sandstone Member of the Cutler Formation (Baker, 1933, p. 30) has not been identified in the mapped area, although it crops out in Castle Valley a few miles northwest where a 300-foot section is exposed. Boulders of white to pink, quartz pebble conglomerate found in Quaternary gravels on the flanks of North and South Mountains near exposures of limestone beds assigned to the Rico Formation probably were derived from this member. In the Moab region the Cedar Mesa Sandstone Member is overlain by a sequence of red medium-grained sandstone and mudstone, 100 feet thick, which Baker (1933, p. 30) named the Bogus Tongue and which he (1946, p. 43) later changed to Organ Rock Tongue. It is not known whether rocks representing this member are present in the La Sal quadrangle.

Cater (1954b) and Shoemaker (1956a) did not subdivide the Cutler into members in the Gateway-Sinbad Valley area because there the formation is dominantly arkose and conglomerate that thicken from zero along the crest of the Uncompahgre Plateau to several thousands of feet a few miles southwest of the uplift. A well near Gateway, Colo., that penetrated more than 7,800 feet of Cutler before reaching the Precambrian basement suggested to Cater that this thick sequence of beds includes rocks of both Permian (?) and Pennsylvanian age that were deposited as a fanglomerate on the flank of the uplift.

The Cutler Formation varies extremely in thickness in the vicinity of the La Sal quadrangle. East of the quadrangle boundary the well drilled near Bedrock, Colo., penetrated 2,687 feet of arkose and conglomerate which were assigned to the Cutler. To the west, Baker measured 670 feet of Cutler in Lockhart Canyon, 390 feet on the crest of the Cane Creek anticline, and 800 feet south of Indian Creek. Outcrops in Sinbad and Paradox Valleys indicate that the Cutler is, in places, truncated by an unconformity at the base of the Moenkopi or, where the Moenkopi is absent, by an unconformity at the base of the Chinle.

The Cutler Formation is present around North and South Mountains, but its thickness and relationship to the enclosing beds are uncertain. Therefore, the relationships and thicknesses shown on the accompanying maps and sections (pl. 1) are mainly projections based on information obtained in surrounding areas. Deposition of the Cutler in the areas where igneous rocks were later intruded was undoubtedly controlled by preexisting salt domes in the areas of the Paradox Valley-Castle Valley and Moab Valley-Pine Ridge anticlines. Salt uplift and erosion during Moenkopi and Chinle time probably thinned the Cutler along the flanks of folds. Thicker parts were later obscured by the intrusion of Tertiary igneous rocks and subsequent formation of alluvial and landslide deposits.

## TRIASSIC SYSTEM

### LOWER AND MIDDLE(?) TRIASSIC SERIES

#### MOENKOPI FORMATION

The Moenkopi Formation (Ward, 1901) is the oldest formation of Mesozoic age in the La Sal quadrangle. It is composed of evenly bedded shale and mudstone containing numerous ledges of thin-bedded fine-grained red-brown and gray sandstone. Gypsiferous sandstone beds and small seams of gypsum are common. The light chocolate-brown color of the Moenkopi contrasts with the brick red of the overlying Chinle Formation and the pale red and maroon of the underlying Cutler. Ripple marks are the most conspicuous sedimentary structures of the Moenkopi, but fossil mud cracks and raindrop imprints are also present. These structures in conjunction with even, continuous bedding and a great abundance of light-colored mica serve to distinguish the Moenkopi from other formations.

In west-central Colorado, Shoemaker (1956a) and Cater (1954b) divided the Moenkopi into three members which were referred to as the lower, middle, and upper members. Subsequently Shoemaker and Newman (1959) added a fourth member and assigned names which, from oldest to youngest, are the Tenderfoot, Ali Baba, Sewemup, and Pariott Members. These subdivisions of the Moenkopi, however, were not observed within the La Sal quadrangle because, like the older formations discussed, the Moenkopi is poorly exposed. Withington (1956) measured a maximum thickness of 450 feet on the northeast side of Paradox Valley. Shoemaker and Newman (1959) measured a total of 1,265 feet on the east side of Sinbad Valley. The Ayers well 1 near Bedrock, Colo., on the southwest side of Paradox Valley, penetrated 867 feet of beds which were assigned to the Moenkopi. To the west of the La Sal quadrangle, Stewart and Williams (written commun., 1953) measured 272 feet of Moenkopi in Lockhart Canyon, and Stewart and Weir (written commun., 1953) measured 295 feet on the north side of North Sixshooter Peak. On the basis of this evidence, the Moenkopi Formation is estimated to reach a maximum thickness of about 400 feet in the La Sal quadrangle, but it may thin or be absent locally near the igneous and salt intrusions.

### UPPER TRIASSIC SERIES

#### CHINLE FORMATION

The Chinle Formation of Late Triassic age crops out in isolated patches around North and South Mountains of the La Sals and is well exposed in the sides of Sinbad and Paradox Valleys. Along the valley walls the Chinle forms steep slopes, but around the mountains where it is part of the sequence of upturned strata, it is found in the valleys between the igneous rock and the prominent hogback formed by the overlying Wingate Sandstone. In general the Chinle Formation is thickest in the southwestern corner of the mapped area and thins to the northeast. Three miles north of La Sal, Utah, the formation may be as much as 600 feet thick, and in the northwest end of Paradox Valley it is 375 feet thick. In Sinbad Valley, Shoemaker (1956a) measured a maximum of 700 feet of Chinle, but states that in places it wedges out and the Wingate rests on the Hermosa Formation. The varied thicknesses of the Chinle Formation obviously are largely the result of movement of salt during Triassic time.

The formation consists of bright-red and red-brown mudstone and siltstone and sandstone containing lenses of limestone-pebble and mudstone-pebble conglomerate. It rests with unconformity on the Rico, Cutler, and Moenkopi Formations in and adjoining the map area. The Chinle is distinguished from the Moenkopi by a color contrast and by differences in bedding. The beds of the Chinle are irregular, extremely lenticular and discontinuous, in contrast to the uniform bedding in the Moenkopi Formation. The upper contact of the Chinle with the overlying Wingate Sandstone is, in places, gradational, but the formational boundary is usually drawn at the base of the massive cliff-forming eolian sandstone.

Because of the sparsity and discontinuity of outcrops within the quadrangle boundaries, the Chinle was mapped as a single unit. In a few places, however, it is well-enough exposed to be divided into two members. The lower member is dominantly siltstone and contains numerous lenses of sandstone and limestone-pebble conglomerate. The upper unit consists mainly of siltstone containing lenses of fine-grained sandstone and thin-bedded limestone. The following section of the Chinle Formation measured in the canyon about half a mile south of the Valley View mine demonstrates this division and shows that the upper and lower members are of nearly equal thickness.

*Section of the Chinle Formation measured in the northeast corner of sec. 18, T. 48 N., R. 19 W., Montrose County, Colo.*

| | Thickness (feet) |
|---|---|
| Wingate Sandstone. | |
| Chinle Formation: | |
| Upper member: | |
| 20. Sandstone and siltstone, calcareous, reddish-brown, fine-grained, thin-bedded | 5.0 |
| 19. Sandstone and siltstone, reddish-brown; altered to light green in places, very fine grained, finely laminated, flat bedded; ledge former | 6.0 |
| 18. Siltstone, reddish-brown; altered locally to light green | 2.0 |
| 17. Sandstone, silty, slightly calcareous; light brown grading upward to white near top; fine grained; dominantly quartz containing trace of opaque minerals and red and green chert; nodular at top; ledge former | 5.0 |
| 16. Mudstone and siltstone, reddish-brown, flat-bedded | 11.0 |
| 15. Sandstone, calcareous light-brown to light reddish-brown, finely laminated; sparse muscovite on bedding planes; pale-green glauconitelike grains | 2.0 |
| 14. Limestone, silty, light-gray; ledge former | 2.0 |
| 13. Siltstone, calcareous, and silty limestone; light red to light gray; ledge former | 2.2 |
| 12. Quartzite, light-gray to light-green, very fine grained; ledge former | 2.0 |
| 11. Sandstone, silty, brown to orange-brown, fine-grained, flat-bedded; ledge former | 16.5 |
| 10. Siltstone, reddish-brown, flat-bedded | 121.0 |
| Total upper member | 174.7 |
| Lower member: | |
| 9. Sandstone containing conglomeratic lenses, light-gray weathering to yellow-gray; conglomerate pebbles of light-gray limestone and reddish-brown mudstone as much as ½ in. in diameter; matrix very fine to fine grained, flat- and crossbedded; ledge former | 9.0 |
| 8. Siltstone, reddish-brown; mottled to light-green | 56.0 |
| 7. Siltstone and conglomerate, calcareous, reddish-brown to light reddish-brown; mudstone pebbles are reddish brown and chocolate brown as much as 2 inches long; gray limestone pebbles as much as 1 inch long; ledge former | 2.0 |

*Section of the Chinle Formation measured in the northeast corner of sec. 18, T. 48 N., R. 19 W., Montrose County, Colo.*—Continued

| | Thickness (feet) |
|---|---|
| Chinle Formation—Continued | |
| Lower member—Continued | |
| 6. Siltstone; conglomeratic at base; reddish-brown; light green in lower 6–12 in.; conglomerate pebbles are reddish brown and light green, and as much as 1 in. long; base of unit is gently undulatory, flat- and crossbedded; ledge former | 17.5 |
| 5. Siltstone, calcareous; reddish-brown to light-green along some beds and fractures; bedding poorly formed | 106.5 |
| 4. Conglomerate, silty, calcareous; chocolate-brown to gray-green siltstone pebbles as much as ½ in. in diameter; quartz grains very fine to coarse | .8 |
| 3. Sandstone, light-gray to white; weathers to yellowish brown; fine to very fine grained | 5.5 |
| 2. Siltstone, reddish-brown | 1.0 |
| 1. Conglomerate, silty, calcareous, reddish-brown; siltstone pebble | 2.5 |
| Total lower member | 200.8 |
| Total Chinle Formation | 375.5 |
| Cutler Formation (not well exposed). | |

In the La Sal quadrangle the beds of the lower member appear to rest directly on the Cutler Formation, although the Cutler is very poorly exposed. In sec. 6, T. 47 N., R. 19 W., Montrose County, Colo., Chinle strata containing conglomerate lenses composed of granules, pebbles, and cobbles of siltstone, limestone, quartzite, quartz, chert, and silicified wood embedded in a reddish-gray fine-grained sandstone matrix are quite similar to the Moss Back Member described by Stewart and others (1959, p. 512–515). The remainder of the Chinle strata in that locality are predominantly siltstone and some sandstone. This composition suggests a lithofacies change from the dominantly sandstone lithology of the unit in Big Indian Wash area to the southwest. The change may, in part, be responsible for the notable absence of uranium deposits in the Chinle of the Paradox Valley area, in contrast to the numerous deposits in the Chinle of the Lisbon Valley area.

The upper part of the Chinle Formation rests conformably on the lower member and consists of reddish-brown and light-brown, horizontally laminated to very thick bedded siltstone and sandy siltstone, and in places, thin-bedded limestone. These beds are very similar to strata in the Monument Valley region of Utah that Witkind and Thaden (1963, p. 21) named the Church Rock Member, but the authors have made no definite correlation between the two areas.

### GLEN CANYON GROUP (LOWER PART)

The Glen Canyon Group (Gregory and Moore, 1931) comprises, in ascending order, the Wingate Sandstone, the Kayenta Formation, and the Navajo Sandstone. The entire Glen Canyon Group was once considered to be Jurassic(?) in age. The presence of vertebrate fossils of Late Triassic(?) age in the Moenave and Kayenta Formations, which directly overlie the Wingate Sandstone in northern Arizona, and other supporting evidence reported by Harshbarger and others (1957, p. 16, 19) place the Wingate in the Triassic System. Later work by Lewis and others (1961) indicate the Kayenta Formation to be of Late Triassic(?) age, and the Navajo Sandstone to be of the Late Triassic(?) and Jurassic age.

#### WINGATE SANDSTONE

The Wingate Sandstone (Dutton, 1885) is the oldest of the three formations of the Glen Canyon Group and conformably overlies the Chinle Formation. It crops out near the eastern edge of the mapped area in the floor of Roc Creek canyon, in the northwest end of Paradox Valley, and on the southwest edge of Sinbad Valley where it forms a cliff as much as 250 feet high. In the western part of the area it forms the hogbacks which surround the igneous rocks of North and South Mountains.

The Wingate Sandstone is a massive, nearly homogeneous, well-sorted, very fine to fine-grained crossbedded sandstone. On fresh surfaces the sandstone is light brown to nearly white, and on weathered surfaces is stained red to dark brown and streaked with black desert varnish. Where the standstone forms cliffs, it is cut by vertical joints that extend from top to bottom. Large blocks spall from the sandstone along the joints and form deposits of talus on the steep slopes of the underlying Chinle Formation. From a distance the bedding in the Wingate is obscured by closely spaced joints and the dark color of the weathered surface. In detail the formation is composed of many horizontal layers of sandstone, ranging thickness from 2 to 50 feet, each of which contains sweeping tangential crossbeds of eolian origin. These sandstone layers are a favorable host for ore minerals derived from ascending hydrothermal solutions, as shown by the presence of the Cashin, Cliffdweller, and Sunrise copper deposits and other copper prospects in the Wingate Sandstone of the Paradox Valley area.

The Wingate ranges in thickness from 280 feet in the northwest part of the map area to 150 feet in the east. Shoemaker (1956a) and Withington (1956) found that the thickness differs most in the vicinity of the salt anticlines—a feature that indicates minor movements of salt of the Hermosa Formation before, during, or shortly following deposition of the Wingate Sandstone.

### UPPER TRIASSIC(?) SERIES

### GLEN CANYON GROUP (MIDDLE PART)

#### KAYENTA FORMATION

The Kayenta Formation (Baker, 1933) rests on the Wingate Sandstone and is usually recognized by marked changes in bedding, color, and resistance to weathering. The beds above and below the contact are virtually conformable and, in places, grade into each other.

The Kayenta Formation crops out in a series of ledges and benches formed by the erosion of lenticular sandstone interbedded with minor amounts of siltstone, thin-bedded shale, and conglomerate. The sandstone is red, buff, gray, or lavender and is composed of fine- to coarse-grained rounded to subrounded quartz grains and minor quantities of mica, feldspar, and dark minerals. The sandstone is typically thin bedded and flaggy; crossbedded and massive lenses, however, are not uncommon. The red siltstone and shale beds, being less resistant to erosion, are found in the recesses beneath overhanging ledges of sandstone and conglomerate. The conglomerate contains angular to rounded pebbles of sandstone, shale, and limestone as much as 2 inches in diameter.

The Kayenta Formation is 160 feet thick on the south flank of South Mountain and 165 feet thick on the south flank of North Mountain. Along Roc Creek and in Paradox Valley it ranges in thickness from 140 to 260 feet. These apparent differences in thickness may be due largely to the fact that in some areas the Wingate-Kayenta contact is well marked and easily distinguished but in other areas, where the two formations interfinger, the contact has been located arbitrarily.

A study of sedimentary structures and feldspar content by Stewart and others (1959) and studies of grain size and mica content by Dane (1935, p. 77, 82) indicate that the Kayenta is of fluvial origin. The formation probably was derived from the ancestral Uncompahgre highland to the northeast and also from an area beyond the line of pinchout in southwestern Colorado (Craig and Dickey, 1956, p. 95).

### TRIASSIC(?) AND JURASSIC SYSTEMS

### GLEN CANYON GROUP (UPPER PART)

#### NAVAJO SANDSTONE

The Navajo Sandstone (Gregory, 1917, p. 57) of Triassic(?) and Jurassic age (Lewis and others, 1961) is the upper formation of the Glen Canyon Group and conformably overlies the Kayenta Formation. It crops out as steep cliffs and rounded slopes in Coyote Wash and La Sal Creek and their tributary canyons in the southern part of the mapped area, at the northwest end of Paradox Valley, in Roc Creek, and in Sinbad Valley. It is also exposed in the hogbacks on the flanks of North and South Mountains. Rock rubble of Navajo lithology in the Middle Mountain area indicates that the formation may have once cropped out there as isolated patches.

The Navajo is light-gray to pale-brown massive, medium- to fine-grained sandstone. It is usually distinguished from other formations by its color and large-scale tangential crossbeds which are often accentuated in relief on weathered surfaces. The sandstone consists of rounded to subrounded grains of quartz and minor quantities of feldspar and dark minerals. The rock weathers readily to sand because the grains are weakly cemented.

The character of the crossbedding and the sparcity of other sedimentary structures indicating water-laid deposits suggest that the Navajo is dominantly of eolian origin. Poole and Williams (1956) believe that the winds transporting this material came from the northwest. Large-scale distortion and crumpling of Navajo beds, thought to be of water-laid origin as noted by Kiersch (1950, p. 939–942) in the San Rafael Swell, Utah, were not recognized in the La Sal quadrangle. Water-laid deposits of the Navajo were recognized, however, in the hogback on the south flank of North Mountain (sec. 36, T. 26 S., R. 24 E., San Juan County, Utah) where the sandstone is 22 feet thick. About 17 feet above the base is a lenticular unit ranging from 0 to 2 feet in thickness that is composed of a fine-grained limy sandstone and locally contains elongate, irregularly shaped masses of white and yellowish-brown to yellowish-gray chert. The masses range in length from a fraction of an inch to 1 foot and lie along horizontal, minutely crumpled bedding planes of the sandstone. Shoemaker (1956a) reports similar deposits of chert in close proximity to a 6-foot bed of limestone at the southwest end of Sewemup Mesa in the Roc Creek quadrangle, just east of the La Sal quadrangle.

The Navajo Sandstone ranges in thickness from 0 in the adjacent Paradox quadrangle (Withington, 1956) on the east to 240 feet along La Sal Creek near Sharp Canyon. To the north on the south flank of North Mountain it is 22 feet thick and has a maximum thickness of 100 feet along Roc Creek. These thickness differences indicate irregular and abrupt thinning and pinching out along the Paradox Valley-Castle Valley anticlinal structure and reflect areas where salt movement, probably in separate domelike cells, was most active prior to or during deposition of the Navajo Sandstone.

## JURASSIC SYSTEM

### SAN RAFAEL GROUP

The San Rafael Group of Middle and Late Jurassic age was first described by Gilluly and Reeside (1928, p. 73) as comprising, in ascending order, the Carmel Formation, the Entrada Sandstone, and the Summerville Formation. Fieldwork in the La Sal quadrangle indicated that, if present, the Carmel Formation is different lithologically from typical Carmel in western Utah and too thin to be mapped as a separate unit. Later regional studies of the San Rafael Group in adjacent areas by Wright and others (1962, p. 2057) showed that Carmel-like earthy siltstone and sandstone beds should actually be considered as facies of the Entrada Sandstone. Wright and his coworkers redefined the Entrada by dividing it into three members that are, in ascending order, the Dewey Bridge Member, the Slick Rock Member, and the Moab Sandstone Member. Inasmuch as these divisions agree with equivalent lithologic units in the La Sal quadrangle, the names proposed by Wright and others (1962, p. 2057) have been adopted in this report, although the Entrada is shown on the map as a single unit. The San Rafael Group, therefore, includes only the Entrada Sandstone and Summerville Formation in the La Sal quadrangle.

#### ENTRADA SANDSTONE

The Entrada Sandstone is a cliff-forming rock unit that crops out in Coyote Wash in the southeast corner of the quadrangle and to the north in Sharp Canyon, La Sal Creek Canyon, at the northwest end of Paradox Valley, in Roc Creek Canyon, and in Sinbad Valley. On the west it crops out in hogbacks around the North and South Mountains, on Mount Peale, and at the headwaters of Twomile Creek.

The base of the Entrada Sandstone is a distinct, even erosion surface which, in most places, truncates cross-strata of the underlying Navajo Sandstone. The contact is especially well exposed in the La Sal Creek Canyon near the east boundary of the map where the Dewey Bridge Member pinches out and the Slick Rock Member rests directly on the Navajo Sandstone. There, the contact is a sharp, even surface overlain by a thin bed of sandstone containing rounded pebbles of black chert and subangular fragments of silicified white sandstone obviously derived from the underlying Navajo Sandstone. Wright and others (1962, p. 2060–2061) mapped a sharp unconformity at the base of the Entrada in the Colorado River Valley at the Utah-Colorado line. This unconformity continues to the east, and Entrada rests on progressively older formations, until in the Black Canyon area of the Gunnison River it rests directly on the Precambrian (Craig and Dickey, 1956, p. 97).

The Dewey Bridge Member consists of reddish-brown to white and buff, horizontally bedded siltstone, mudstone, and sandstone within the La Sal quadrangle. Sandstone is predominant and is composed of layers of very fine and fine-grained, fairly well sorted quartz grains and abundant interstitial clay and thin red clay partings. In places the sandstone is poorly sorted and contains grains of medium size. Weak cementation in areas of poor sorting results in differential weathering of the rock, and the layers form rounded ledges and nodules separated by shallow recesses. In places thin layers of crossbedded sandstone are interstratified with thin flat-bedded units. Locally the basal beds consist of black and gray chert pebbles and reworked Navajo Sandstone in angular fragments as much as 1 foot in length. These sandstone fragments and chert pebbles are sufficiently abundant locally to form layers of conglomerate. A notable example of this conglomerate is in the canyon of West Paradox Creek at the northwest end of Paradox Valley.

The Dewey Bridge Member ranges in thickness from 0 to 66 feet, and probably represents subaqueous deposition in a marginal marine environment (Gilluly and Reeside, 1928, p. 75; Baker, 1946, p. 74–75); it may be equivalent in time of deposition to the Carmel of western Utah. No fossils have been found in these beds within the map area.

The Slick Rock Member, like the Wingate and Navajo Formations, is a massive sandstone, but unlike these formations, it differs in color from place to place. Known locally as the "Slick Rim," the Slick Rock Member crops out as smoothly rounded orange, buff, and white cliffs spotted by horizontal rows of pits resulting from differential weathering. It is well exposed in La Sal Creek Canyon and the canyons to the south, at the head of Paradox Valley and near Buckeye Reservoir, and in Roc Creek Canyon and Sinbad Valley. It is also exposed on the top and sides of Mount Peale.

The upper and lower parts of the Entrada Sandstone are largely horizontally bedded units suggestive of subaqueous deposition; these two parts are separated by a middle unit consisting of tangentially crossbedded sandstone. The middle unit is dominantly of eolian origin (Stokes and Holmes, 1954, p. 37). The Entrada Sandstone differs from the somewhat similar Wingate and Navajo Formations by the sorting of sand into two distinct grain sizes, both of which are generally coarser than those of the older formations. The bulk of the sandstone is composed of subrounded to subangular fine grains of quartz, usually less than 0.15 mm in diameter, which are weakly cemented by calcium carbonate. Larger grains, generally distributed along bedding planes in thin layers, range from 0.4 to 0.8 mm in diameter, are frosted, and display excellent sphericity. These grains, sometimes referred to as "Entrada berries" are distinctive of the unit and were of considerable aid in determining the presence and position of the Entrada in the mountainous parts of the area.

The Moab Sandstone Member, within the map area, is red to gray and, in places, is white, horizontally bedded sandstone that ranges in thickness from 0 to 40 feet along Roc Creek and from 40 to 100 feet near Geyser Pass. This unit, originally referred to as the Moab Tongue (Baker, 1933, p. 49), is separated from the rest of the Entrada Sandstone by a distinctive horizontal bedding plane. The unit is sometimes coarser grained and more friable than the underlying crossbedded sandstone and differs from the Moab Tongue of the type area by the general absence of crossbedding.

The following section of the Entrada Sandstone measured in La Sal Creek Canyon (secs. 28 and 33, T. 28 S., R. 26 E., San Juan County, Utah) by L. C. Craig and others (written commun., 1948) illustrates this relationship. The revised nomenclature of Wright and others (1962) is shown in parentheses.

| | Thickness (feet) |
|---|---|
| Summerville Formation. | |
| Entrada Sandstone: | |
| Moab tongue(?) (Moab Sandstone Member): | |
| 16. Interval covered except upper 1 ft. Sandstone, white, very fine grained; contains rare pink accessory minerals | 4.0 |
| 15. Sandstone, white to pale-brown; weathers pale brown; fine to very fine grained; composed of clear quartz and moderate amount of pink accessory minerals; unlaminated, structureless | 5.7 |
| 14. Claystone, dark-red, silty and sandy, very poorly sorted; grains range from very fine to medium-fine; weathers shaly to rounded | 6.4 |
| Total Moab Tongue(?) (Moab Member(?)) | 16.1 |
| "Slick Rim" Member (Slick Rock Member): | |
| 13. Sandstone, white to pale-yellow; weathers buff to light gray; fine to medium-fine grained; composed of rounded clear quartz and rare pink and black accessory minerals; horizontal ridging suggests bedding; unlaminated | 38.1 |
| 12. Sandstone, light-buff to white, fine to medium-fine grained; fair sorting; thin-bedded with tangential cross lamination | 5.9 |
| 11. Sandstone, buff to white, fine to medium-fine grained; composed of clear quartz and minor white chert and colored accessory minerals; highly cross laminated; no "Entrada berries" | 51.1 |

Entrada Sandstone—Continued

"Slick Rim" Member (Slick Rock Member)—Con.

| | Thickness (feet) |
|---|---|
| 10. Sandstone, brownish-buff, fine to medium-fine grained; composed of clear quartz and "Entrada berries"; long-radius cross lamination; thickly bedded | 41.6 |
| 9. Sandstone, orange-buff; some red bands; composition as in unit 8; cross laminated, wedge bedded | 8.8 |
| 8. Sandstone, orange-buff, fine-grained; composed of clear quartz and some white chert; "Entrada berries" of medium-coarse to medium, rounded and frosted clear quartz and white and red chert; cross laminated; wedge bedded | 41.8 |
| 7. Sandstone, red, very fine to fine-grained, well sorted; composed of rounded clear quartz and minor subangular white chert; some red clay laminae | 5.4 |
| 6. Sandstone, white below, orange-buff above, fine-grained, poorly sorted; composed of clear quartz and disseminated medium to medium-coarse frosted clear quartz; white and gray chert and some subangular white chert; long-radius cross lamination | 16.2 |
| Total "Slick Rim" Member (Slick Rock Member) | 208.9 |
| Dewey Bridge Member: | |
| 5. Sandstone, dark-red to buff to white, interbedded; very fine and fine-grained, fairly well-sorted sand containing abundant thin red clay partings and fine to medium-fine-grained, poorly sorted sand | 30.7 |
| 4. Sandstone, brown, very fine to fine-grained, poorly sorted; composed of subangular to rounded clear quartz and numerous large granules of angular white chert as much as 1 inch in diameter | 1.4 |
| Total Dewey Bridge Member | 32.1 |
| Total Entrada Sandstone | 257,1 |

Navajo Sandstone.

The average thickness of the Moab Member throughout the area is generally less than 40 feet, and because it crops out as part of a steep cliff, making a narrow outcrop in plan, it is undifferentiated from the rest of the Entrada on the maps. The total thickness of the Entrada Sandstone, including the Moab Tongue, ranges from 200 to 310 feet. Differences in thickness depend largely on the thickness of the Moab Member.

## CONTACT OF THE ENTRADA SANDSTONE AND SUMMERVILLE FORMATION

The top of the Entrada Sandstone within the La Sal quadrangle is almost everywhere a distinctive smooth surface on which the Summerville Formation conformably lies. In spite of this generally well-defined contact, deposition of the Entrada and Summerville probably was contemporaneous in some places. This relation is illustrated near the pinchout of the Moab Tongue in Roc Creek Canyon. There, the Moab Tongue grades laterally into the Summerville Formation (Shoemaker, 1956a), and locally the contact of the Entrada and Summerville is not always on the same surface or horizon. In general, however, the contact is uniform and readily recognized over most of the area; it was, therefore, used as the structure-contour horizon.



## SUMMERVILLE FORMATION

The Summerville Formation (Gilluly and Reeside, 1928, p. 79–80), the uppermost formation of the San Rafael Group, is exposed in the same areas described for the Entrada Sandstone. The Summerville Formation generally crops out as a steep red earthy or debris-covered slope or a finely banded cliff. It consists predominantly of reddish-brown thin, evenly bedded mudstone and shale and some interbedded light-gray to light-brown platy to slabby fine-grained sandstone. Asymmetrical ripple marks are fairly common in the sandstone beds. Thin discontinuous beds of dark-gray dense limestone occur in the upper part of the formation. Locally these beds are fractured and filled with carnelian veinlets. In general, the lower part of the formation has more abundant and thicker sandstone beds than the upper part. A tripart division of the Summerville Formation is illustrated in the following section measured just south of the map area.

*Section of the Summerville Formation half a mile north of Coyote Wash and 1 mile east of the Utah-Colorado line in an unsurveyed part of T. 46 N., R. 20 W., Montrose County, Colo.*

[Measured by J. L. Gualtieri and W. R. Barton]

Morrison Formation.

Summerville Formation:

| | Thickness (feet) |
|---|---|
| 6. Interval poorly exposed. Dominantly interbedded pale-red and reddish-brown mudstone and siltstone. Some thin flat-bedded sandstone composed of white to light gray to pale red, very fine to fine-grained subrounded to rounded quartz and gray and brown accessory minerals, probably chert | 39.5 |
| 5. Sandstone, pinkish-gray, yellowish-gray, and pale-red; weathers to pale reddish brown; spotted with limonitic fine-grained well-sorted subrounded to rounded transparent to translucent quartz and gray, black and brown chert grains; flat bedded; increasingly well cemented toward top; surface weathers to concretionlike nodules | 21.0 |
| 4. Interval poorly exposed. Interbedded pale reddish-brown fine- to medium-fine-grained sandstone, siltstone and mudstone; subrounded quartz grains and gray and brown accessory minerals | 51.0 |
| Total thickness of Summerville Formation | 111.5 |

Entrada Sandstone.

The Summerville Formation ranges in thickness from 65 feet in La Sal Creek Canyon to 140 feet in the upper canyon of Roc Creek (Shoemaker, 1956a). The greatest local variations in thickness are due to erosion marked by sandstone-filled paleostream channels at the base of the overlying Morrison Formation.

#### MORRISON FORMATION

The Morrison Formation (Cross, 1894a, p. 2) of Late Jurassic age is about 700 feet thick in the La Sal quadrangle. It is composed of two members of approximately equal thickness, the older Salt Wash Member and the younger Brushy Basin Member. The base of the Morrison Formation, according to Craig and others (1955, p. 134), is defined as the base of the fluvial Jurassic deposits overlying beds of the San Rafael Group that are of marine or marginal marine origin. In the La Sal quadrangle this contact was mapped at the base of the lowermost continuous sandstone bed of the Salt Wash Member which rests on the eroded surface of the Summerville Formation. This surface is mainly flat, but locally may be slightly irregular or show a well-defined channeled scour. In places, a light-gray to white limestone bed, a few inches to a few feet thick, occurs at the base of the Morrison Formation. In other places an orange-red to milky-white chert bed of similar thickness is found. The top of the Morrison Formation is placed at the base of the massive conglomeratic sandstone of the Burro Canyon Formation of Early Cretaceous age. The Burro Canyon is easily recognized for it crops out as a prominent cliff in the high mesas surrounding La Sal Creek Canyon. The contact of the Burro Canyon with the Morrison Formation is rarely seen, however, because it is generally obscured by landslide deposits and vegetation. Where exposed, the sandstone of the Burro Canyon makes a well-defined contact with the variegated shale and mudstone of the Brush Basin Member.

##### SALT WASH MEMBER

The Salt Wash Member (Lupton, 1914, p. 127; Gilluly and Reeside, 1928, p. 82; Craig and others, 1955, p. 135) is composed of interstratified lenses of sandstone and mudstone. In the mapped area, it ranges in thickness from 250 to 350 feet, and can be roughly divided into three lithologic units, each of which has a lenticular sandstone at the base, overlain by interbedded siltstone and mudstone. The sandstone beds of the basal unit form the first continuous ledge above the top of the Entrada Formation. The sandstone beds of the middle unit, being highly lenticular and discontinuous, form a prominent ledge only where they are thickest. The uppermost sandstone strata, although highly lenticular, usually crop out as a distinctive ledge that forms a prominent bench on many mesas.

The sandstone strata are reddish- to light-brown, very pale orange, grayish-yellow, and white fine- to medium-grained beds composed of clear quartz and minor amounts of white, pink, and green chert, clear feldspar, black opaque minerals, and interstitial clay The quartz grains are subrounded to rounded and generally well sorted. The chert grains are angular to subrounded and are generally slightly larger than the quartz grains. Calcite is the principal cementing material. Limonite is present in places as specks between or coating on the sand grains; limonite diffusion bands impregnate sandstone locally. Fossil logs and dinosaur bones are found in places in the sandstone.

Interstratified siltstone and mudstone separate sandstone strata and also occur within the sandstone as thin lenses, films, and fragments ranging in size from pebble to cobble. The fact that the fragments are angular to rounded probably reflects the distance of transport and the amount of abrasion by Salt Wash streams. The siltstone and mudstone are dominantly reddish brown but in places are gray or greenish gray. The reason for this color difference is not well understood, but the occurrence is significant because of its relationship to uranium deposits. In many places near uranium-vanadium deposits the red mudstone appears to have been altered to greenish gray directly beneath, within, and sometimes above mineralized sandstone. A. D. Weeks (written commun., 1951) suggests that a chemical reaction took place under reducing conditions which decreased the total iron content and the ferric-ferrous iron ratio and changed the color of the clay from red to greenish gray.

*The ore-bearing sandstone.*—Most of the uranium-vanadium deposits in the La Sal Creek area are in the uppermost continuous sandstone strata of the Salt Wash. This unit is commonly called the ore-bearing sandstone or third rim, in reference to its position above the Entrada Sandstone.

The ore-bearing sandstone is, in some places, composed of a single broad lens of cross-laminated sandstone ranging from 0 to 30 feet in thickness. In other places it is composed of many overlapping sandstone lenses which have a combined total thickness of 30 to 105 feet. The cross-laminated sandstone appears to have been deposited in a flood-plain environment. The overlapping lenses are channel deposits in which scour-and-fill bedding is common. Scour-and-fill bedding of the festoon type consists of crossbedded sandstone lenses truncated by and in direct contact with other truncated lenses, or separated from them by thin, discontinuous mudstone lenses or mudstone conglomerate. Fragments of fossil wood are abundant in these scour-and-fill beds and occur either along the bedding planes or in podlike masses called "trash pockets."

In places, the ore-bearing sandstone was deposited in channels cut in the underlying mudstone. These are generally broad features which rarely exceed a depth of 10 feet but which locally may be as much as 20 feet deep where narrow scours are cut into the underlying rock. Away from the channels the ore-bearing sandstone may pinch out into interstratified layers of reddish-brown claystone, reddish-gray limestone, and fine-grained orthoquartzite. These rocks indicate that a lacustrine or flood-plain environment existed along the margins of stream channels. Local ponding within the channels is indicated by sand-filled dessication cracks in mudstone layers that separate the sandstone lenses. Such features were observed in the Evening Star and Gray Daun mines.

The trends of sedimentary structures such as cross-bedding, current lineation, and ripple marks indicate that the streams which deposited the ore-bearing sandstone flowed generally eastward in the La Sal Creek area. Fossil logs are generally oriented parallel to the trend of paleostream flow.

#### BRUSHY BASIN MEMBER

The Brushy Basin Member (Gregory, 1938, p. 59) is composed of variegated siltstone, mudstone, bentonitic clay, and minor amounts of sandstone and conglomerate. It ranges in thickness from 250 to 400 feet and crops out as gentle slopes and steep, rounded hills on the bench formed by the underlying Salt Wash Member. It is recognized by its contrasting colors of red, light greenish gray, and purple.

A lenticular conglomeratic sandstone containing red, green, white, and black chert pebbles usually marks the base of the Brushy Basin Member throughout most of the mapped area. Because of the variety of color in the pebble assemblage, this unit is locally referred to as the "Christmas tree conglomerate." It ranges from 0 to 70 feet in thickness and is usually separated from the ore-bearing sandstone of the Salt Wash by layers of mudstone and siltstone that increase in thickness where the conglomerate thins. In places the conglomerate rests directly on the ore-bearing sandstone. The conglomerate is distinguished from the ore-bearing sandstone by its assemblage of red and green pebbles, by its coarser grain size, and locally by a higher percentage of interstitial clay. Uranium deposits in the Brushy Basin are rare, erratically distributed, and generally associated with the basal conglomerate or similar units found higher in the member. Typical examples are at the Hesperus and Sumner mines on La Sal Creek and the Too High mine on the south side of Wray Mesa.

Petrified dinosaur bones and wood are common in the Brushy Basin Member. A fossil tooth, found on Wray Mesa by LeRoy Bennett of Grand Junction, Colo., was studied by G. Edward Lewis of the U.S. Geological Survey. Lewis believes it probably belongs to either the genus *Apatosaurus* (*Brontosaurus*) or *Camarasaurus* (*Morosaurus*), both of which are Archosauria of the Order Saurischia and Suborder Sauropoda. Lewis stipulates that a definite generic classification cannot be made on the basis of a single tooth. The relative abundance of saurian fossils, the presence of thin limestone beds, and the marked decrease in the amount of sandstone in the Brushy Basin Member suggest that it was deposited in a lacustrine environment, possibly under a more humid climate than that of the Salt Wash Member.

The following section of the Morrison Formation was measured on the north side of La Sal Creek Canyon in secs. 28 and 33, T. 28 S., R. 26 E., San Juan County, Utah, by L. C. Craig and others (written commun., 1948). Subsequent sections measured in the La Sal quadrangle and cores from drill holes indicate that the lithologies described here are representative, although the contact between the Brushy Basin and Salt Wash Members may differ as much as 50 feet from the contact shown here.

| | Thickness (feet) |
|---|---|
| Burro Canyon Formation. | |
| Morrison Formation: | |
| Brushy Basin Member: | |
| 47. Claystone, light-green; weathers to copper-green; sandy; contains disseminated fine- to medium-grained rounded clear quartz | 12.0 |
| 46. Interval with scattered exposure. Claystone is dark red, maroon and chocolate brown, silty to sandy; a few thin 2-ft ledges of dark-red siltstone | 132.2 |
| 45. Interval very poorly exposed. Probably gray shale and sandstone interbedded. Shale is light greenish gray. Sandstone dark green, fine grained; composed of clear quartz, siliceous cement; forms several ledges 1 to 2 ft thick | 166.0 |
| 44. Interval poorly exposed. Siltstone, claystone, and sandstone interbedded. Predominantly red and green silty to sandy claystone and a few thin interbeds of dark-red mottled siltstone and very fine grained sandstone | 21.6 |
| 43. Sandstone and shale. Sandstone, white to pale-brown, fine grained; contains abundant orange, red, and green chert as accessory minerals | 13.6 |
| Total Brushy Basin Member | 345.4 |

Morrison Formation—Continued
Salt Wash Member:

| | Thickness (feet) |
|---|---|
| 42. Claystone, dark-red to gray, silty to fine-grained, sandy; contains several thin beds of pink to white fine-grained, ripple-laminated to structureless sandstone | 8.5 |
| 41. Sandstone, white and pale-brown, fine-grained; faintly cross laminated. (Upper ledge of ore-bearing sandstone unit.) | 10.3 |
| 40. Interval poorly exposed. Sandstone and sandy claystone; unit is mainly very fine to fine-grained sandstone containing grading and variable amounts of clay | 19.8 |
| 39. Sandstone, white to pale-brown; weathers light gray to pale brown; fine to medium fine grained; composed of subrounded clear quartz and abundant green, white, and tan subangular chert and minor pink, gray, and black grains; channeling, cross laminated. (Base of ore-bearing sandstone unit.) | 17.6 |
| 38. Interval poorly exposed. Claystone to sandstone interbedded. Claystone, dark red, maroon, and reddish brown, silty. Sandstone pink to white and green, very fine to fine-grained, in part ripple laminated | 52.0 |
| 37. Sandstone, white; weathers light gray; very fine grained; structureless | 2.2 |
| 36. Sandstone and claystone interbedded. Sandstone pink, weathers red brown; very fine grained; ripple laminated. Claystone dark red, slightly silty; earthy weathering | 5.1 |
| 35. Sandstone, white; weathers light gray to pale brown; medium-fine to medium-grained; composed of subrounded clear quartz containing minor pink, gray and black, quartz, and white to tan angular chert | 16.2 |
| 34. Claystone, dark-red, slightly silty; friable to earthy weathering | 14.2 |
| 33. Sandstone, white; weathers light gray; very fine to fine-grained; composed of subangular clear quartz and accessory minerals; faintly laminated | 3.2 |
| 32. Claystone and sandstone interbedded. Claystone dark red to purple, in part slightly silty. Sandstone pinkish, very fine grained; ripple laminated; in beds as much as 6 in. thick | 15.5 |
| 31. Sandstone, white to pale-brown, very fine to medium-fine grained; composed of clear quartz and minor accessory minerals; faintly variegated laminations with minor channeling | 11.8 |
| 30. Interval covered. Float indicates dark red, slightly silty claystone, and interbeds of reddish-brown and white, very fine grained sandstone | 38.2 |
| 29. Sandstone, pink to white; weathers light reddish brown; very fine to fine-grained; composed of subangular clear quartz and minor pink and black accessory minerals; indistinct lamination, minor channeling | 11.2 |
| 28. Interval covered. Float indicates claystone, dark-red, slightly silty | 27.8 |

Morrison Formation—Continued
Salt Wash Member—Continued

| | Thickness (feet) |
|---|---|
| 27. Sandstone, white; weathers grayish brown; very fine grained; composed of subangular clear quartz and minor pink, black, and gray accessory minerals; evenly bedded, not prominently laminated | 1.3 |
| 26. Interval covered. Float indicates dark-red, silty to fine-grained sandy claystone; weathers to chips and earthy fragments | 19.1 |
| 25. Sandstone, pale-brown, fine- to medium-fine-grained; composed of subangular clear quartz and variegated accessory minerals; highly cross laminated, channeled | 21.7 |
| 24. Sandstone and claystone. Sandstone pink to purplish-pink, fine to medium grained, poorly sorted; grades to dark-red sandy claystone; bedding poorly defined | 3.3 |
| 23. Sandstone, slightly conglomeratic, white; weathers light gray to pale brown; fine to medium grained; moderate sorting; composed of subangular to rounded clear quartz and abundant white to tan angular chert and minor variegated accessory minerals; highly cross laminated; channelled; conglomerate contains white chert pebbles as much as ½ in. in diameter | 11.9 |
| 22. Claystone and sandstone interbedded. Claystone dark-red, very silty to sandy; medium-fine-grained, poorly sorted. Sandstone white to reddish brown, very fine to medium fine, well sorted; composed of clear quartz and minor variegated accessory minerals | 15.0 |
| 21. Sandstone, white to pale-brown; weathers reddish brown; medium-fine grained; composed of subangular clear quartz and numerous variegated accessory minerals; abundant white chert grains; highly cross laminated; channel | 27.2 |
| Total Salt Wash Member | 353.1 |
| Total Morrison Formation | 698.5 |

Summerville Formation.

## CRETACEOUS SYSTEM

### LOWER CRETACEOUS SERIES

#### BURRO CANYON FORMATION

The Burro Canyon Formation, originally described as a separate formation by Coffin (1921) who called it Post-McElmo, was defined by Stokes and Phoenix (1948) as the beds separating the Morrison Formation of Jurassic age from the Dakota Sandstone of Late Cretaceous age in southwestern Colorado and southeastern Utah. Stratigraphic position and fossil evidence (Brown, 1950; Katich, 1951; Stokes, 1952; Simmons, 1957) indicate that the Burro Canyon is of Early Cretaceous age.

West of the Colorado River in Utah there are beds of somewhat similar lithology and the same age as the

Burro Canyon which Stokes (1944) named the Buckhorn Conglomerate and the Cedar Mountain Formation.

In the mapped area the Burro Canyon Formation contains a basal unit, approximately 110 feet thick, that is light-gray to light-brown, medium- to coarse-grained crossbedded sandstone containing pebble-conglomerate lenses and sparse silicified logs. This basal unit conformably overlies the variegated shale and mudstone units of the Brushy Basin Member of the Morrison Formation. The sandstone commonly crops out as a prominent cliff and forms mesas. In many places the basal sandstone is overlain by a sequence of light-green mudstone, siltstone, and shale containing thin beds of siliceous limestone, limestone pebble-conglomerate, limy sandstone, chert and orthoquartzite; the sequence aggregates 150 feet in thickness. Where present, these strata distinguish the Burro Canyon Formation from the overlying Dakota Sandstone. The maximum thickness of the Burro Canyon Formation in the mapped area is about 260 feet, as shown in the following section measured near Pine Ridge in secs. 1 and 12, T. 28 S., R. 25 E., San Juan County, Utah. Color designations are after Goddard and others (1948).

Dakota Sandstone. Conglomerate at base rests on erosion surface.

| Burro Canyon Formation: | Thickness (feet) |
|---|---|
| 6. Most of unit covered by thin veneer of alluvium. Light-green to gray-green mudstone; contains thin-bedded sandstone, limestone, and chert as much as 1.5 ft thick. Light-gray impure, marly and dense limestone; sandy in part; contains fine to medium-fine grains of quartz. Light and dark-gray and green thin-bedded dense chert. Unit forms very gentle slope that steepens near base of the Dakota Sandstone | 99.0 |
| 5. Sandstone, in part conglomeratic and in part contains limestone nodules; white (*N* 9) to very light gray (*N* 8) and very pale orange (10*YR* 8/2); weathers to brownish gray (5*YR* 4/1) and light olive gray (5*Y* 5/2); fine to medium subangular to well-rounded, moderately frosted, fair- to well-sorted quartz grains, sparse opaque minerals, and limonite spotting. Conglomerate pebbles are light-gray, orange-yellow, and dark-gray to black chert, subrounded, to 8 mm in diameter, average 5 mm. Beds are chiefly massive. Forms ledge on gentle slope | 11.0 |
| 4. Covered interval. Probably mudstone much like that described in unit 6 | 2.5 |
| 3. Sandstone, white (*N* 9) to very light gray (*N* 8); medium-fine- to medium-coarse-grained, subangular to well-rounded, poorly sorted quartz cemented by secondary silica and spotted with limonite; very sparse green mudstone films on bedding planes; flat bedded to massive. Forms thin ledges in slope | 6.5 |

| Burro Canyon Formation—Continued | Thickness (feet) |
|---|---|
| 2. Covered interval. Probably mudstone like that described in unit 6. Forms gentle slope | 23.5 |
| 1. Sandstone and conglomeratic sandstone, grayish-orange (10*YR* 7/4), dark yellowish-orange-brown (10*YR* 6/6), and light brown (5*YR* 5/6); weathers to dark yellowish brown (10*YR* 4/2); medium-fine to coarse, subangular to well-rounded quartz grains, sparse white opaque minerals, interstitial mudstone, and abundant limonite spotting. Chert pebbles occur in thin coarse-grained sandstone lenses scattered along bedding planes; range from 1 to 3 cm but average 5 mm in diameter. Bedding intricate; torrential and gently sweeping cross-beds; in places flat bedded and massive. Unit forms prominent cliff | 110.0 |
| Total thickness | 252.5 |

Basal contact covered.

Morrison Formation (Brushy Basin Member).

Although not present in the measured section, a bed as much as 8 feet thick of light-gray well-indurated fine-grained orthoquartzite that is overlain by the Dakota Sandstone crops out a few hundred feet to the west. Here and elsewhere in the mapped area the orthoquartzite bed appears to be the uppermost unit of the Burro Canyon Formation. In it are spheroidal structures having concentric crack systems formed around irregular nodular cores of light blue-gray chert. Such cores, according to Pettijohn (1949, p. 149–150), result from the local concentration of silica in a sandstone unit during epigenetic replacement of carbonate cement. Subsequently, after the sandstone has become quartzite, dehydration of the silica body causes the host rock to shrink and form concentric crack systems known as contraction spheroids. This phenomenon is common in the orthoquartzite bed, both around chert nodules and elsewhere in the unit.

Silicification of the standstone to form quartzite occurred prior to deposition of the overlying formations, as noted in the following discussion of the Burro Canyon-Dakota contact. Inasmuch as this quartzite is the uppermost unit of the Burro Canyon Formation, lithifying processes are presumed to have been active during a period of nondeposition under subaerial weathering conditions. The duration of this hiatus is not yet determined.

### BURRO CANYON-DAKOTA CONTACT

The Burro Canyon-Dakota contact in the La Sal quadrangle is extremely undulatory (Carter, 1957). Where the orthoquartzite bed at the top of the Burro Canyon Formation is present, it is conformably overlain by lenses of conglomerate and sandstone of the basal unit of the Dakota Sandstone. Where the orthoquartzite is absent, the base of the Dakota conglomerate is in contact with successively lower beds of the Burro Canyon—light-green mudstone, limestone, and chert—and defines broad conglomerate-filled channels. In many places the Dakota is in contact with the thick conglomeratic sandstone which is the basal unit of the Burro Canyon (fig. 2).

Previous workers have described the Burro Canyon-Dakota contact as an angular unconformity between the beds above and below the erosion surface, but no angular relations or wedging out were observed, except locally, in the La Sal quadrangle. Therefore the term "disconformity" is used to describe the contact in this area. In outcrop, the disconformity is in places obscure and, because of its undulatory nature, is difficult to trace. Where the basal conglomerate of the Dakota Sandstone rests on the basal sandstone unit of the Burro Canyon, the contact may be distinguished from a distance by a color contrast, that is, the gray sandstone of the Burro Canyon is overlain by conglomeratic sandstone beds in the Dakota that range from yellow brown to pale orange brown. Near the outcrop this color contrast is less conspicuous. Where the Burro Canyon is bleached immediately below its contact with the Dakota, the contact is obvious. Bleached zones range in thickness from a few inches to several feet and are typified by rock that is poorly cemented and extremely friable. Where the contact is stratigraphically higher—that is, on the mudstone and limestone of the upper part of the Burro Canyon—it is easily identified, for conglomerate of the Dakota forms a ledge 1 to 20 feet thick.

## UPPER CRETACEOUS SERIES

### DAKOTA SANDSTONE

The Dakota Sandstone in the La Sal quadrangle rests on the eroded surface of the Burro Canyon Formation and is overlain by the Mancos Shale of Late Cretaceous age. The strata comprising the Dakota Sandstone can generally be divided into three parts: (1) a basal unit of sandstone and conglomerate, (2) a middle unit of gray carbonaceous shale containing discontinuous coal seams, and (3) an upper unit of sandstone. Where all three units are present, the formation has an aggregate thickness that ranges from 150 to 200 feet. The contact

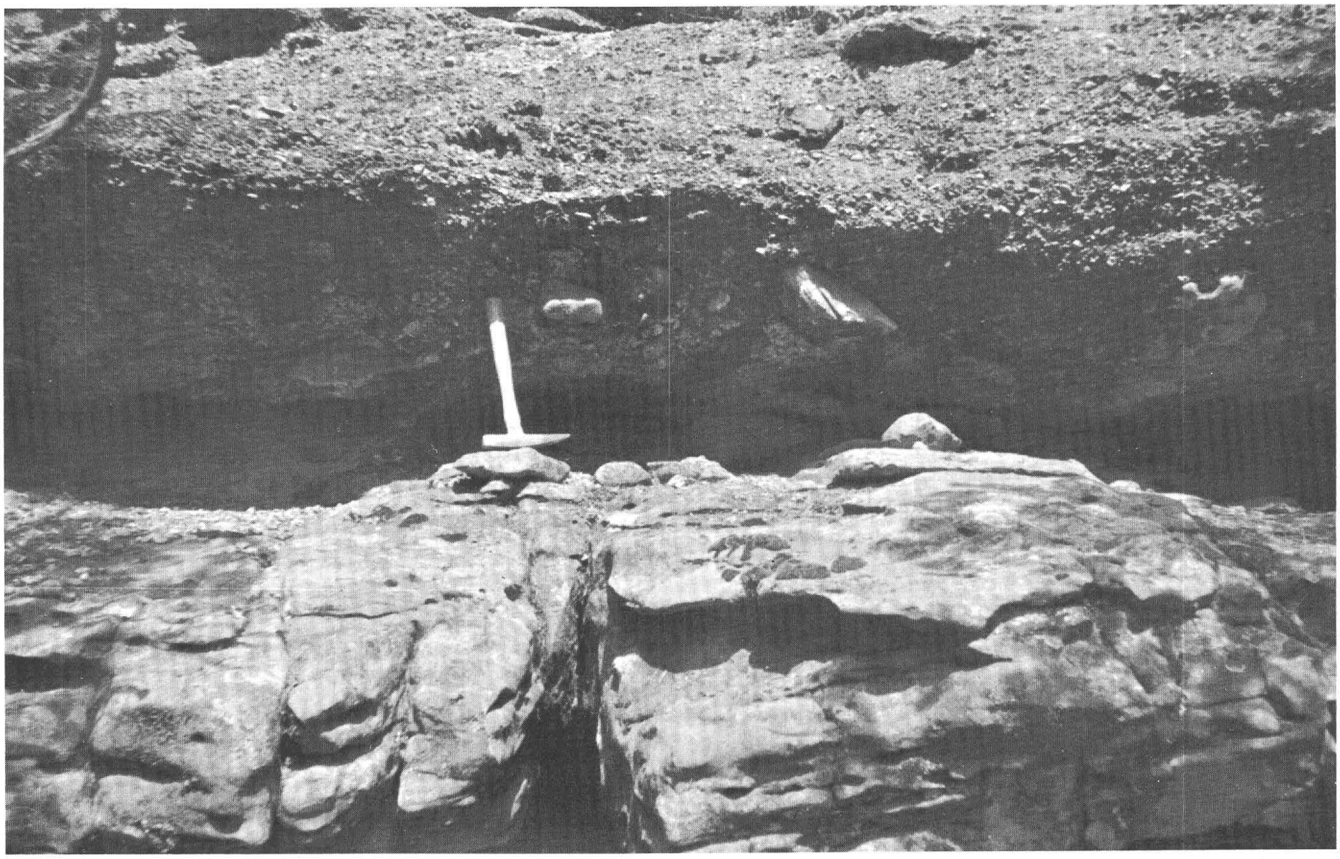


FIGURE 2.—Conglomerate in the Dakota Sandstone containing quartzite and sandstone boulders resting on sandstone which is the basal unit of the Burro Canyon Formation. Locality is on Wray Mesa, north of Coyote Wash, San Juan County, Utah.

with the overlying Mancos is generally covered in the mapped area.

The basal unit ranges in thickness from a few inches to more than 60 feet and crops out as a ledge which commonly forms the cap of mesas. It is composed of yellow-brown to light orange-brown medium-grained sandstone that is characterized in many places by overlapping lentils of sandstone 4 inches to 2 feet thick. Many of these lentils contain inclined beds of sandstone which dip from 20° to 40°. The basal sandstone unit contains sparse to abundant plant debris that is carbonaceous or has been replaced by limonite. These fossils are considered to be of Late Cretaceous age (Brown, 1950, p. 47) and help to distinguish the Dakota from the Burro Canyon Formation.

In many places sandstone of the basal unit contains discontinuous lenses of coarse conglomerate and sandstone. The conglomerate is composed of rounded and subrounded pebbles of gray and black chert, milky quartz, and gray quartzite ranging in diameter from 5 mm to 5 cm. Local concentrations of angular and subangular cobbles and boulders of sandstone, quartzite, and chert are found at the base of the sandstone or conglomerate. These fragments are lithologically identical to rocks of the Burro Canyon Formation from which they were undoubtedly removed and redeposited in channels cut by the same streams that deposited the basal unit of the Dakota Sandstone. In places the conglomerate is very poorly cemented and extremely friable; elsewhere it contains great quantities of silica cement and is well indurated. Where present this conglomerate forms a distinctive base for the sequence of beds comprising the Dakota Sandstone.

In the mapped area these basal conglomerates of the Dakota fill broad depressions or channels in the Burro Canyon Formation that are more than 100 feet deep, several thousand feet wide, and of unknown length. Measurements of current lineation, crossbeds, and festoons indicate that the trend of these channels differs from place to place, but in general is N. 30° E. Poorly preserved fossils in the chert pebbles of the conglomerate have been tentatively identified as of Permian or Pennsylvanian age. Some forms are similar to fossils found in the Kaibab Limestone, and L. C. Craig (oral commun., 1957) suggests a source area that lies to the southwest. Such a source agrees with measurements of sedimentary structures in the conglomerate beds that form the base of the Dakota Sandstone.

The basal unit grades upward into and in places interfingers with the middle unit; a unit composed of light-gray carbonaceous shale, siltstone, and mudstone which have a total thickness of approximately 100 feet. Coal seams, generally less than 3 feet thick, occur at various levels throughout the unit. In outcrop the high carbon content, which serves to distinguish it from the underlying Burro Canyon Formation, imparts a gray color to the formation.

The upper unit is a light-brown medium- to fine-grained sandstone which crops out as ledges 10 to 30 feet high. Both inclined and flat bedding are common throughout the upper sandstone unit.

The following detailed section of the Dakota Sandstone is taken from a core obtained in drill hole LC371 (collar elevation: 7,365.8 ft) in sec. 29, T. 28 S., R. 26 E., San Juan County, Utah, on Hideout Mesa, north of La Sal Creek Canyon. The lithologies are described here in much more detail than they are normally seen in outcrop and are considered to be typical of the Dakota Sandstone in the mapped area.

Erosion surface. Mancos Shale absent.

| Dakota Sandstone: | *Thickness (feet)* |
|---|---|
| 28. Sandstone, light-brown, medium-fine- to medium-grained; abundant opaque minerals and limonite spots; sparse brown mudstone pellets, torrential crossbedding separated by flat-bedded sandstone. Forms ledge in nearby outcrop | 18.4 |
| 27. Mudstone, interbedded brown and gray layers; gypsiferous, mostly in fractures | .6 |
| 26. Shale; interbedded black and gray layers, carbonaceous | 13.3 |
| 25. Lignite, black. Abundant gray mudstone mixed with coal and in thin seams | 2.8 |
| 24. Shale, black, fissile. Limonite stain along bedding planes | 5.0 |
| 23. Sandstone, light-brown to brown, fine-grained; abundant opaque minerals and limonite spots; sparse carbon. Abundant carbonaceous mudstone along bedding planes. Flat bedded | 2.3 |
| 22. Siltstone, light-gray and black; abundant carbon | .3 |
| 21. Sandstone, light-brown, fine-grained; abundant limonite and opaque minerals; abundant carbon and carbonaceous mudstone as films and seams along bedding planes; flat bedded. Interbedded with black carbonaceous mudstone | 1.7 |
| 20. Sandstone, brown, fine-grained; abundant limonite spots and opaque minerals. Sparse carbon and carbonaceous mudstone as films on bedding planes | .6 |
| 19. Shale, gray | .9 |
| 18. Lignite, black | 1.0 |
| 17. Shale, gray; slightly carbonaceous. Gypsum fills joints | 2.5 |
| 16. Sandstone, light-gray to white, very fine to medium-fine-grained; abundant white opaque minerals; sparse carbon flecks and interstitial gray mudstone | 1.3 |
| 15. Shale, gray slightly carbonaceous | 12.1 |

| Dakota Sandstone—Continued | *Thickness (feet)* |
|---|---|
| 14. Siltstone; light-gray layers interbedded with black layers; sparse carbon; abundant carbonaceous mudstone films and seams; contorted and crinkled bedding | 14.8 |
| 13. Sandstone, light-brown, fine-grained; abundant limonite spots, sparse carbon, and gray mudstone pellets and films | 5.0 |
| 12. Mudstone and siltstone, interbedded, gray; sparse carbon | 2.4 |
| 11. Shale, dark-gray to black; abundant carbon, coaly in part | .8 |
| 10. Siltstone, gray to light-gray; sparse marcasite and carbon | 15.8 |
| 9. Sandstone, light-brown to gray, medium-fine to medium-grained. Sparse gypsum, very sparse carbon, and sparse gray mudstone filling interstices, also as seams and pellets | 3.9 |
| 8. Siltstone, dark-gray to brown, sandy; sparse carbon | .3 |
| 7. Mudstone, greenish-gray; sparse carbon, fossil plants | .7 |
| 6. Mudstone, gray; thin seams of gypsum | 4.8 |
| 5. Mudstone, light-gray; sparse pyrite and bentonite | 1.7 |
| 4. Siltstone, gray, very carbonaceous; sparse marcasite in radiating crystals around a black carbonaceous core; 0.3 ft of limonite stain at base | 1.8 |
| 3. Siltstone, sandy; light-brown to light-gray; sparse carbon and gypsum. Abundant interstitial greenish-gray mudstone; also as seams and pellets | 1.8 |
| 2. Sandstone, light-brown, medium- to medium-coarse-grained; sparse white opaque minerals, very sparse carbon, sparse whitish mudstone pellets; clean, poorly cemented. (Forms ledge in nearby outcrop.) | 31.6 |
| 1. Sandstone, conglomeratic, light-brown to light-gray, coarse-grained; conglomerate pebbles of green and white chert; abundant gray mudstone pellets. (Forms ledge in nearby outcrop) | 3.5 |
| Total Dakota Sandstone | 151.7+ |

Burro Canyon Formation.

In the section above, the Dakota Sandstone rests on bluish-green mudstone of the upper member of the Burro Canyon Formation. Along the west side of Hideout Mesa, not far from the drill hole from which the core described in the section was taken the Burro Canyon-Dakota contact is well exposed and clearly illustrates the features described in preceding paragraphs. At the southern end of Hideout Mesa the sandstone and conglomerate beds of the Dakota rest directly on the massive sandstone of the Burro Canyon. From there the contact rises stratigraphically to the north.

### MANCOS SHALE

The Mancos Shale (Cross, 1899, p. 4), youngest of the Mesozoic sedimentary rocks in the La Sal quadrangle, rests conformably on the Dakota Sandstone. The Mancos is best exposed along Geyser Creek west of its confluence with Deep Creek at the head of Roc Creek Canyon. The Mancos also crops out in Geyser Pass, around Mount Mellenthin, and in a large area extending from La Sal Pass southeastward to the head of Pole Spring Canyon. Both areas are extensively covered by glacial and landslide debris. An isolated exposure was found at the top of a downdropped block of sedimentary rock in the collapsed area at the northwest end of Paradox Valley. The Mancos crops out as somber gray rounded hillocks and steep slopes, generally barren of vegetation. Weathering of the shale surface produces an efflorescent covering of light-gray clay that is sometimes several inches thick and extremely sticky and slippery when wet.

The Mancos is composed of dark-gray fissile marine shale and thin beds of light-gray siltstone, limy siltstone, petroliferous limestone, and limestone nodules. The limy units contain an abundant faunal assemblage. Thin coquina beds of oyster shell (*Ostrea Congesta* Conrad) are associated with shale zones that contain irregular seams and pods of prismatic aragonite, many of which appear to have replaced fossil shells.

The general homogeneity of the Mancos, possible concealed structural deformation, and the absence of continuous exposures make it difficult to determine accurate thicknesses of the formation or to differentiate between its members. No complete section of the Mancos is known to exist in the mapped area; erosion has removed most of the beds. Measurable thicknesses of the formation differ from a few feet to several hundred feet. In places the apparent thickness differences are the result of ice action which locally contorted the beds during the glacial epoch. The greatest thickness of Mancos, an estimated 1,000 to 1,200 feet, is partly exposed along Geyser Creek in the Taylor Creek syncline. Field identification of the faunal assemblage found here suggests that the shales have an age range equivalent to that of the Greenhorn, Carlile, and Niobrara Formations of the Western Interior.

Rocks of an age equivalent to the age of the Tununk Shale Member of Gilbert (1877, p. 4) are recognized by the presence of *Gryphaea newberryi* which occurs throughout the area in the lower 100 feet of the Mancos. These strata correlate with the Greenhorn Limestone of the western part of the Interior Plains. About 500 feet above the base of the Mancos is a thin zone of coquina and limestone beds containing abundant fauna, among which are *Prionocyclus wyomingensis*, *Scaphites warreni*, *Inoceramus dimidius* and *Lopha lugubrius*. All are of late Carlile age and are in the Ferron Sandstone Member of the Mancos, which is absent here but present a few miles west of the mapped area (Baker, 1933, p. 55). This thin zone, less than 10 feet thick, is probably equivalent to the Ferron. *Inoceramus deformis* and *Ostrea congesta* of Niobrara age are indicative of the Blue Gate Shale Member of Gilbert (1877, p. 4), with which the remainder of the Mancos in the La Sal quadrangle is tentatively correlated. Further, more detailed, paleontological studies are needed in this locality.

The base of the Mancos is not exposed throughout most of the area. Where exposed, the contact is well defined by shale resting conformably on the upper sandstone strata of the Dakota or locally on a thin sequence of light-gray to black carbonaceous mudstone beds that overlie the upper sandstone of the Dakota. On the south side of Mount Mellenthin a conglomerate bed about 2 feet thick occurs at the base of the Mancos. The matrix is dark gray and is composed of fine- to coarse-grained quartz and interstitial carbonaceous clay. The pebbles range from 2 mm to 1 cm in diameter and are composed of rounded light-gray chert and dark-gray carbonaceous mudstone galls. Although the geographical distribution of such conglomeratic lenses is not known, it appears that the upper part of the Dakota Sandstone was, in places, reworked by the encroaching sea in which the Mancos was deposited.

## TERTIARY(?) SYSTEM

### GEYSER CREEK FANGLOMERATE

Sedimentary rocks of Tertiary age which crop out in the Book Cliffs, north of the mapped area, are absent in the La Sal quadrangle. Local deposits of Tertiary(?) fanglomerate, however, occur on the flanks of the La Sal Mountains. Baker (1933, p. 56) describes consolidated gravel resting on folded Mancos Shale on the ridge between upper Pack Creek and upper Cane Creek on the west flank of South Mountain. Hunt (1956, p. 30) describes a deposit of fanglomerate that rests directly on salt of the Hermosa Formation in Castle Valley and is downfolded as the result of removal of salt.

A deposit of fanglomerate similar to that described by Hunt (1956) was found in the northern part of the La Sal quadrangle and the southern part of the Polar Mesa quadrangle. It was first recognized on the ridge between Geyser Creek and Deep Creek (sec. 36, T. 26 S., R. 25 E., Grand County, Utah) and has been named Geyser Creek Fanglomerate by Carter and Gualtieri (1965). The unit is also well exposed on the north side of Deep Creek Canyon in the same general area.

The Geyser Creek Fanglomerate is a consolidated conglomeratic sandstone, cemented with calcium carbonate, that rests with angular unconformity on the folded Mancos Shale. The Mancos Shale crops out along the margins of a narrow northwest-trending structural trough known as the Taylor Creek syncline which occupies the area between the collapsed anticline of Sinbad Valley and North Mountain. The center of the trough is filled with the conglomerate which crops out as vertical cliffs and steep slopes (figs. 3, 4).

The conglomerate may be roughly divided into two lithologic units. The lower unit, resting on the Mancos Shale, is composed of yellowish-gray to grayish-orange, very fine grained thin-bedded silty sandstone, interstratified with sandy siltstone and claystone beds. These beds are poorly cemented and very friable, and contain abundant fragments of aragonite and fossil shells undoubtedly derived from the underlying Mancos. This zone, 4 to 15 feet thick, rests with angular unconformity on the Mancos. It is conformably overlain by, and in places interfingers with, interstratified layers of sandstone and conglomerate. The sandstone is composed of fine-grained quartz and interstitial clay particles and cemented with calcium carbonate. The conglomerate beds are lenticular and composed of sandstone and igneous pebbles and boulders. The pebbles, generally 2 inches in diameter or less, comprise the bulk of conglomeratic material. Boulders as much as 2 feet in diameter occur in the thicker lenses. Most of the older formations exposed in the area are represented by the sandstone pebbles and boulders and can be recognized by their distinctive lithologic characteristics. In general, they appear to show an inverted age relation, as would be expected in the normal cycle of erosion and deposition. For example, the sandstone and conglomerate of the Upper Jurassic Morrison Formation and Lower Cretaceous Burro Canyon Formation are represented as pebbles and boulders in the lower part of the conglomerate. Pebbles and boulders in the upper part are derived dominantly from Middle and Lower Jurassic and Triassic rocks. Boulders of sandstone and conglomerate derived from the Kayenta Formation are most easily recognized. Igneous boulders in the deposit show various degrees of alteration due to weathering. Many appear relatively fresh while others are highly weathered to yellowish brown or bright orange brown owing to alteration of the mafic minerals to limonite. The igneous boulders also appear to increase in number as well as in average size from bottom to top. This variation may reflect either the increasing size of the igneous source area or a gradual downwarping of the synclinal basin which increased the gradient and transporting capacity of the streams. In the upper unit, fossil fragments derived from the Mancos decrease in abundance toward the top. These features are demonstrated in the following geologic section.

777-039 O—65——4

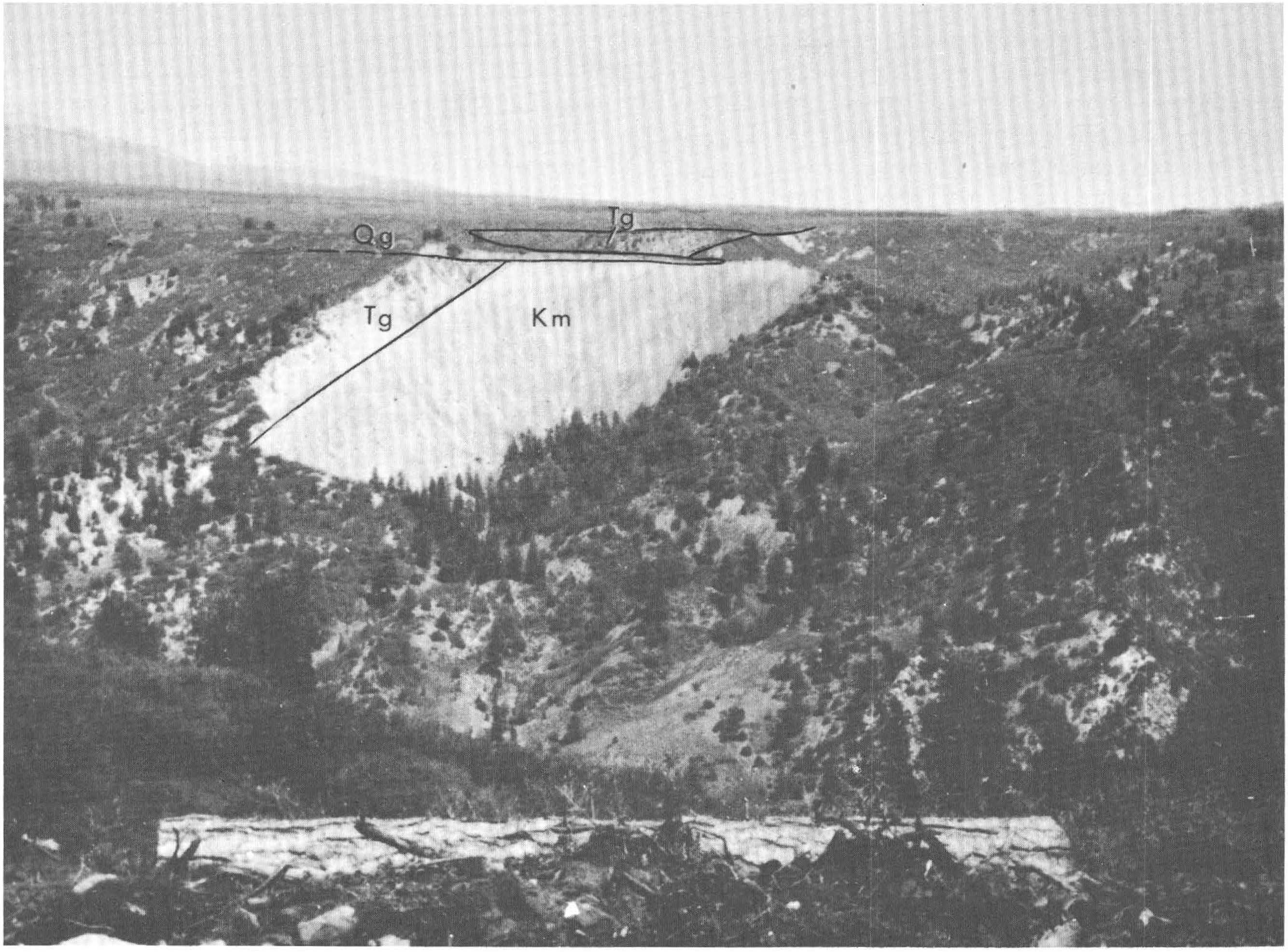



FIGURE 3.—Outcrop of Geyser Creek Fanglomerate. Conglomerate (Tg) resting on Mancos Shale (Km) in SE¼ sec. 36, T. 26 S., R. 25 E., San Juan County, Utah. Both dip westward (left side of picture) and are truncated by an erosion surface on which Quaternary terrace gravel (Qg) has been deposited.

*Measured section at type locality of the Geyser Creek Fanglomerate exposed on the north side of Deep Creek in NE¼ sec. 36, T. 26 S., R. 25 E., Grand County, Utah*

| | *Thickness (feet)* |
|---|---|
| Quaternary gravel. | |
| Geyser Creek Fanglomerate: | |
| 14. Conglomerate, light-brown; diorite porphyry and sandstone boulders as much as 1.5 ft long, 0.9 ft wide, 0.7 ft thick in fine-grained sandstone matrix cemented with calcium carbonate; layer near base contains pebbles as much as 3 in. long, encrusted with $CaCO_3$; interiors of pebbles completely weathered to soft powdery limonite. Sparse aragonite fragments. Forms ledge | 7.5 |
| 13. Sandstone, grayish-orange-pink, very fine to coarse-grained, poorly sorted; 80–90 percent rounded quartz grains; remainder composed of black and brown chert grains and angular to subangular aragonite fragments | 1.5 |
| 12. Conglomerate, light-brown; diorite porphyry and sandstone boulders as much as 1 ft in diameter; sparse pebbles of limestone; sandstone boulders are composed of fine-grained light-gray quartz sandstone resembling Wingate sandstone. Upper 5 ft partly covered. Forms ledge | 8.0 |
| 11. Interval covered by talus and loose gravel | 16.5 |
| 10. Conglomerate and interbedded conglomeratic sandstone, light-brown, fine- to coarse-grained, poorly sorted; cemented with $CaCO_3$; 30 percent is diorite porphyry boulders as much as 2 ft in diameter, weathered to various degrees. Thirty percent is sandstone boulders and pebbles of lavender to red-brown sandstone (Kayenta Formation), light-gray to light-brown fine-grained sandstone (Wingate Sandstone), and red-brown to reddish-orange and brown silty sandstone (Chinle Formation). Twenty percent is composed of dark-gray limestone and siltstone pebbles as much as 1 in. in diameter (Mancos Shale), light-gray fine-grained sandstone and light-green and red chert (Morrison Formation), white to light-gray fine-grained quartzite (Burro Canyon Formation). Twenty percent is unindentified. Forms cliff | 24.0 |

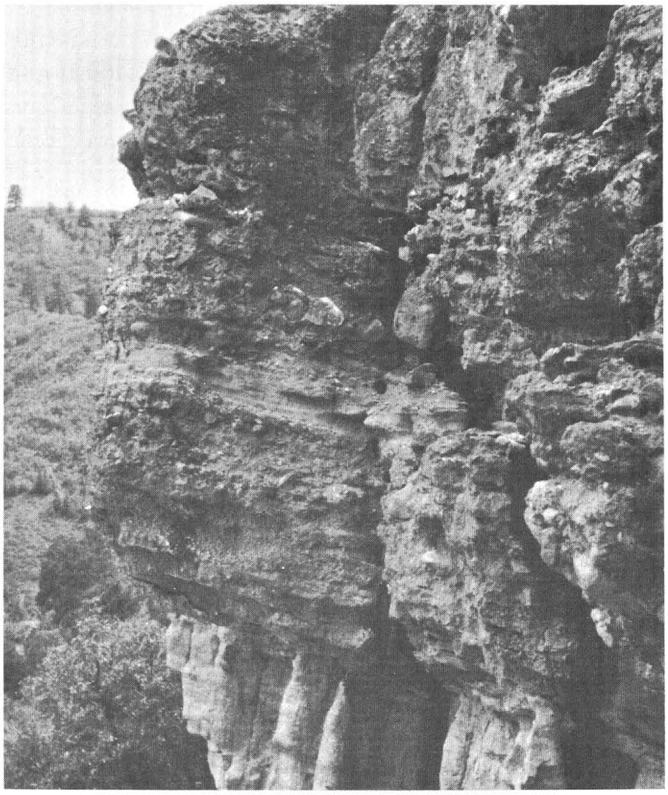


FIGURE 4.—Outcrop of conglomerate at type section on Deep Creek in NE¼ sec. 36, T. 26 S., R. 25 E., San Juan County, Utah, showing zone of reworked fossiliferous Mancos Shale in sandstone at base, overlain by well-cemented sandstone and conglomerate lenses. Beds dip westward toward their mountain source at an angle of about 25°. Outcrop shown is about 12 feet high.

| Geyser Creek Fanglomerate—Continued | *Thickness (feet)* |
|---|---|
| 9. Conglomerate with pebbles and cobbles of diorite porphyry and sandstone; pebbles average 2 in. in diameter, cobbles as much as 6 in.; some silty sandstone pebbles impregnated with limonite. Well cemented. Forms protruding ledge | 2.0 |
| 8. Sandstone, light-brown, flat-bedded to crossbedded, fine- to coarse-grained; poorly sorted quartz grains, coarse-grained opaque minerals, and angular fragments of feldspar. Scattered pebbles of diorite porphyry, sandstone, and siltstone. Differences in cementation of beds causes differential weathering to series of rounded ledges and recesses | 9.0 |
| 7. Conglomerate and sandstone, interbedded lentils. Conglomerate lenses composed of pebbles and cobbles as much as 4 in. in diameter, average 1–2 in. in diameter; poorly cemented, friable. Diorite porphyry pebbles, slightly altered by weathering, make up 50 percent of conglomerate; sandstone and siltstone pebbles form remainder. Sandstone lenses are light brown, very fine grained to silty; contain scattered coarse grains of quartz; well cemented with $CaCO_3$; weather to protruding rounded ledges | 8.5 |

| Geyser Creek Fanglomerate—Continued | *Thickness (feet)* |
|---|---|
| 6. Conglomerate, light-brown, poorly sorted; sandstone matrix is very fine to coarse-grained. Pebbles as much as 3 in. in diameter, rounded, dominantly sandstone and red siltstone. Some impregnated with limonite; powdery | 1.0 |
| 5. Conglomerate, light-brown, poorly sorted, weakly cemented; crossbedded at base, flat-bedded near top; pebbles range from 1 in. in diameter to boulders 18 in. across. Sandstone pebbles and boulders dominant; diorite porphyry detritus less than 10 percent. Silty sandstone pebbles impregnated with limonite | 11.5 |
| 4. Sandstone, conglomeratic, light-green to yellowish-brown, flat-bedded and crossbedded, fine-grained; contains some coarse lenses; coarse lenses contain scattered pebbles as much as 2 in. in diameter. Limonitic stain at base | 4.5 |
| 3. Conglomerate, light-brown; pebbles and cobbles averaging 2–3 in. in diameter, boulders as much as 2 ft long; coarser material in upper 3 ft; sandstone boulders dominant. Flat-bedded and crossbedded; limonite stain throughout; cementing and induration variable | 6.0 |
| 2. Siltstone, sandy, light-green to red-brown; massive and thin flat-bedded layers extremely friable, weakly cemented. Abundant fossil and aragonite fragments derived from Mancos Shale | 6.0 |
| 1. Conglomerate, light-brown; pebbles, cobbles and boulders. Sandstone pebbles as much as ¼ in. in diameter dominant; sandstone boulders as much as 18 in. in diameter; a few diorite porphyry pebbles; angular fragments of aragonite. Limonite-stained sandstone lens near base of unit; basal contact obscured by talus composed of shell and aragonite fragments in a matrix of light-green powdery clay and fine-grained sandstone believed to be reworked zone on the Mancos | 10.0 |
| Total thickness of the conglomerate of the Deep Creek area | 116.0 |

Unconformity.
Mancos Shale.

The Geyser Creek fanglomerate ranges in thickness from 0 near the La Sal Mountains to an estimated 600 feet in the center of the synclinal trough and is 50 to 120 feet thick along its eastern limit. The top of the formation has been beveled by erosion and is overlain by unconsolidated terrace gravel of Quaternary age that average about 40 feet in thickness (fig. 3). Richmond (1962) has referred the terrace gravels to the oldest deposits in the Harpole Mesa Formation, glacial drift of probably Nebraskan (earliest Pleistocene) age. The fanglomerate, therefore, is pre-Quaternary and probably of late Pliocene age although no fossils have yet been found to substantiate this assumed age.

One of the more interesting features of the Geyser Creek fanglomerate is its structural relationship with the underlying Mancos Shale along the east flank of the Taylor Creek syncline. This relationship and its implication are discussed in the section describing the Taylor Creek syncline (p. 27).

### QUATERNARY SYSTEM

Quaternary deposits ranging in age from Pleistocene to Recent are widespread in the La Sal quadrangle. These deposits include a great variety of unconsolidated debris of diverse origin which indicate an interesting history of climatic change, erosion, and deposition in and adjacent to the La Sal Mountains. This history is the subject of a report by G. M. Richmond (1962) of the U.S. Geological Survey. The oldest of these deposits are of glacial and periglacial origin and are within and on the flanks of the mountains. Younger deposits of alluvium and colluvium occur on the canyon and valley floors, eolian deposits and residual soils on the mesas and uplands. On the map of the La Sal quadrangle these deposits have been classified in six groups although, in many places, they grade into each other and are not easily separable. These groups are glacial moraines, rock glaciers, rubble, fan gravel, landslides, and loess alluvium. Glacial moraines include all deposits which can be directly attributed to a glacial origin; these are discussed in greater detail in succeeding paragraphs. Rock glaciers are few in number, of smaller extent, and appear to be of postglacial age. They are nearly free of vegetation and can be distinguished by their lobate plan and a surface composed of a series of somewhat concentric ridges. Rubble deposits are sheetlike masses mainly composed of blocky and slabby fragments of igneous rock, and locally of resistant sandstone. The contacts of rubble deposits with igneous rocks and landslide deposits are indefinite. In the areas of Mount Peale and Mount Mellenthin where rubble deposits are contiguous with rock glaciers, they were mapped as such. Boulders and coarse gravel form fan-shaped or apronlike deposits at the mouths of the mountain canyons. Landslide deposits include talus and talus cones, hummocky deposits of boulders, slump blocks, and all other colluvial debris of irregular form found in the mountains, around mesas, and in the canyons. Loess alluvium includes stream-deposited silt, sand, and gravel and wind-blown silt and sand.

The most outstanding and readily recognized glacial features in the La Sal Mountains are the cirques and U-shaped valleys of the Middle Mountain group. Within and extending from them are deposits composed mostly of unconsolidated igneous rock debris occurring as moraines, outwash plains, and erratics. Lateral and medial moraines occupy the cirques and U-shaped valleys in the higher elevations and, although they have been considerably modified by erosion, can be traced to lower elevations within a 4-mile radius of the mountains. Terminal and recessional moraines are narrow ridges extending perpendicular to the direction of ice flow. These ridges have steeply inclined slopes on their distal side; the proximal side is gentle and marked by deep lakes, or in places, coalescent ponds and grassy meadows. A notable example of a terminal moraine is southwest of Geyser Creek in sec. 9, T. 27 S., R. 25 E., San Juan County, Utah. Here recessional moraines have created Blue and Dark Canyon lakes as well as many other deep pothole lakes that are typical of glaciated terrain. Glacial erratics, some as large as 20 feet long, 10 feet wide, and 10 feet thick, are common throughout the area extending from La Sal Pass to Pole Spring Canyon.

The glacial deposits of pre-Wisconsin, Wisconsin, and Recent age have been mapped in detail by Richmond (1962) who divided them into four formations representing four major stages of glaciation. These are, from oldest to youngest, the Harpole Mesa Formation of pre-Wisconsin age, the Placer Creek Formation of early Wisconsin age, the Beaver Basin Formation of late Wisconsin age, and the Gold Basin Formation of Recent age. Each formation records several episodes of glacial advance and recession. Study of the Harpole Mesa Formation enabled Richmond to estimate that the ice covered a maximum of 85 square miles and that its maximum thickness was 400 feet. During this stage, ice of three glacial advances covered most of the mountain area. The advances are tentatively correlated with the Nebraskan, Kansan, and Illinoian advances of the mid-continent region. Richmond believes that during the first recession of the ice there was partial subsidence of the Castle Valley anticline and that during the second recession Moab and Castle Valleys were partly excavated. The third recession was accompanied by a gradual regional uplift; the subsequent recessions brought further subsidence and excavation of the previously mentioned areas and also of Sinbad and Paradox Valleys.

Richmond (1962, p. 101–102) states that carbon-14 age determinations indicate that deposition of the Gold Basin Formation of Recent age began about 2,900 years ago and came to an end about 1860. During this period the receding glaciers partly filled most of the cirques, and the timberline was about the same as it is today (11,000 to 11,500 ft above sea level). In general the climate was somewhat cooler and wetter than at the present time.

## IGNEOUS ROCKS

The igneous rocks of the La Sal Mountains have been studied by Peale and J. A. Holmes (in Peale, 1877a,b), Cross (1894b), Hill (1913), Gould (1926), and more recently by Hunt and Waters (Hunt, 1958). Because these rocks had been studied in considerable detail, the authors made only cursory examinations, mostly in areas where the igneous rock affected the surrounding sedimentary rocks. Of special interest was the possible relationship of igneous rock to uranium-vanadium deposits; consequently a summary of previous petrographic and chemical work and additional information the authors believe pertinent is given here.

The igneous rocks of the La Sal Mountains are intrusive and are constituted almost entirely of diorite porphyry and lesser amounts of monzonite and syenite porphyries, intruded in the order listed (Waters, 1955, p. 715–716). In the La Sal quadrangle, diorite porphyry is the principal intrusive rock; it crops out in three areas along the northern and western margins of the map. These three areas are parts of the three intrusive centers that form the mountain groups comprising the La Sal Mountains. Hunt (1958) referred to the three groups as North Mountain, Middle Mountain, and South Mountain, and these designations are used in this report. Of the North Mountain group only the southern part of Mount Tomasaki and the southeastern part of Haystack Mountain lie within the quadrangle. Mount Mellenthin and Mount Peale comprise the eastern half of the Middle Mountain group and lie near the northwest edge of the map. The southeastern part of South Mountain extends into the west-central part of the area.

### PETROGRAPHY

Gould (1926, p. 80–81) described the megascopic appearance of the diorite porphyry as fine grained, light gray to white, and containing dark phenocrysts of ferromagnesian minerals, light-colored phenocrysts of feldspar, and sparse phenocrysts of quartz imbedded in a light-gray aphanitic groundmass. The ferromagnesian minerals consist almost wholly of hornblende and minor amounts of light-green pyroxene.

Microscopically, Gould (1926, p. 81–82) determined the feldspar phenocrysts to be oligoclase and andesine; albite or more calcic plagioclase are quite rare. The plagioclase forms broad tabular idiomorphic phenocrysts containing albite and showing rare Carlsbad twinning. Zone banding is common. Although rare, orthoclase phenocrysts occur in elongate crystals and commonly display Carlsbad twinning. Quartz is generally associated with feldspar in the groundmass and is rarely found as phenocrysts.

Gould states that hornblende is the most abundant ferromagnesian mineral. It occurs most commonly as the green pleochroic variety with minor amounts of the brown and bluish-green varieties. Hornblende is intimately associated with magnetite, either surrounding magnetite grains or crystals or bordered by magnetite. Pale-green to colorless augite is less common. Biotite is the least abundant of the ferromagnesian minerals and occurs as the brown, strongly pleochroic variety.

Magnetite, already mentioned in connection with hornblende, is the most common accessory mineral. Gould recognized two generations of magnetite but did not indicate any genetic difference. Sphene occurs as widely as magnetite but is less abundant. Apatite is present in all the rocks, whereas zircon is sparsely distributed.

The groundmass of the porphyry is almost entirely quartz and feldspar, usually orthoclase. Gould observed that the texture of the diorite porphyry ranges from microgranular to coarsely crystalline. Hunt (1953, p. 152) noted that in the Henry Mountains the texture of the diorite porphyry differs from one intrusive body to another, but in any one body he found the texture to be uniform. Hunt related this difference to conditions within the magma, because the textural differences appeared to be independent of the size or shape of the intrusive body or nature of the host rock.

Alteration of some of the diorite porphyry rocks from the La Sal Mountains has been reported by Gould. The feldspars are altered to sericite and are associated with smaller amounts of calcite. Some of the ferromagnesian minerals are apparently replaced by colorless or pale green epidote. Hunt and Waters (Hunt, 1958, p. 334–339, 345) found varying degrees of alteration, especially in North Mountain. They recognized that the altered rocks range from slightly altered porphyry in which less than half the hornblende had been affected, the feldspar only incipiently, and the magnetite not at all, to recrystallized porphyry in which new minerals made up a part of the rock. The alteration occurred mainly along joint zones which they attributed to structural adjustments of some laccoliths to later intrusions. The alteration minerals they listed are epidote, pyrite, calcite, quartz, actinolite, hedenbergite, fluorite, clay minerals, sericite, albite, and perthite. The following analyses were given by Hunt (1958, p. 321).

*Chemical analyses of diorite porphyry from the La Sal Mountains*

[From Hunt, 1958, p. 321. Analysts, W. F. Hillebrand (1) and Lucille Kehl (2)]

| | Mount Peale (1) | Mount Tomasaki (2) | | Mount Peale (1) | Mount Tomasaki (2) |
|---|---|---|---|---|---|
| $SiO_2$ | 61.21 | 63.11 | $CO_2$ | 0 | 0.36 |
| $Al_2O_3$ | 17.10 | 16.76 | $P_2O_5$ | .24 | .23 |
| $Fe_2O_3$ | 2.72 | 2.15 | $SO_3$ | 0 | (S).02 |
| FeO | 1.88 | 1.85 | Cl | .04 | 0 |
| MgO | 1.47 | 1.30 | F | 0 | 0 |
| CaO | 4.83 | 3.11 | MnO | .15 | .09 |
| $Na_2O$ | 5.66 | 6.23 | BaO | .13 | .06 |
| $K_2O$ | 3.00 | 3.44 | SrO | .07 | 0 |
| $H_2O$ | .34 | .13 | $Li_2O$ | Tr.(?) | 0 |
| $H_2O+$ | .68 | .43 | | | |
| $TiO_2$ | .51 | .43 | Total | 100.05 | 99.70 |
| $ZrO_2$ | .02 | 0 | | | |

These analyses closely agree with the estimated chemical composition of the average intrusive rock in the laccolithic mountains of the Colorado Plateau (Hunt, 1956, p. 43). Hunt reports that the $Na_20$ and $K_20$ contents in the igneous rocks of the La Sal Mountains are, in general, higher than in 27 other samples from the Henry, La Plata, and other mountains of the Plateau. This variation may be due to the intimate association of the La Sals with the soda- and potash-rich salt anticlines. Late phases of igneous activity in North Mountain, however, produced soda-rich syenite and rhyolite which probably had little or no contact with the salt. Hunt and Waters (Hunt, 1958) believe these later intrusions were more fluid and of higher temperature than the earlier diorite and monzonite porphyries because they contain high-temperature quartz. Hunt (1956, p. 43) states that in North Mountain the latest intrusions breached the surface and erupted explosively; these eruptive rocks contain potash in great excess of soda, in contrast with earlier intrusives.

## INCLUSIONS

Gould (1926, p. 80–81) recognized hornblendic inclusions in the diorite porphyry which he implied were segregations rather than xenoliths. Hunt (1953, p. 160, 164; 1958, p. 349) stated that in the Henry and La Sal Mountains xenoliths from the sedimentary or basement rocks are relatively rare, whereas hornblendic fragments are abundant and comprise 95 percent or more of the inclusions. The authors observed that there is no gradation between xenoliths and hornblendic inclusions. Xenoliths are relatively unaltered and retain their original sedimentary features. They are generally near the contacts of intruded rocks, but inclusions are widespread throughout the igneous masses.

Hunt proposed that the inclusions in the Henry Mountains are fragments of rock derived from great depth, (1) from altered wallrock traversed by the magma, (2) from segregations formed in the magma reservoir, feeder pipes, or laccoliths, or (3) from layers of the substratum from which the magma was derived. Waters (1955, p. 715–716) preferred the third hypothesis. He pointed out that the order of intrusion in the La Sal Mountains was (1) diorite porphyry, (2) monzonite porphyry, (3) syenite porphyry, and (4) feldspathoidal syenite. Noting that the hornblendic inclusions are much more abundant in the diorite than in the other rock types, Waters concluded that the diorite magma was in part a product of partial fusion of amphibolitic rock of which the hornblendic inclusions are fragments. The diorite magma became changed through time by the solution of the unfused inclusions and through filter pressing, produced, in order, the other rock types. Shoemaker (1956b, p. 54) made reference to Waters' idea but also proposed an alternative: the inclusions are cognate and were derived by crystal settling and accumulation of the more basic fraction of the magma from which the rocks of the La Sal Mountains were derived. The escaping acid fraction of the magma carried some of these hornblendic crystal accumulations in to the stocks and laccolithic chambers of the mountains.

## CONTACT METAMORPHISM

Contact metamorphism has played only a minor role in the history of the La Sal Mountains.

Shale and mudstone in contact with igneous rocks are indurated and altered in color. With the exception of a small patch of sedimentary rock on the north side of the Mount Mellenthin laccolith, beds of the Mancos Shale in contact with the igneous rock show little or no color change. In contrast are the mudstone beds of the Morrison Formation that are in contact with the Mount Peale bysmalith. Beds that are normally red have been altered to deep purple and black—a feature that indicates that hematite may have changed to magnetite. Elsewhere red mudstone shows only slight color change at the igneous contact.

The small patch of sedimentary rock on the north side of Mount Mellenthin contains Upper Cretaceous marine fossils and has been mapped as Mancos Shale, but older beds may also be present. Metamorphism has been more extreme here than at any other place observed in the La Sal Mountains. Part of the sedimentary rock has been metamorphosed to hornfels. The present beds retain only a trace of their former bedding and are, of course, no longer fissile. In one place the hornfels is minutely crenulated. In places it contains light-green bands and lenses of calcite, quartz, and irregular to roughly rounded masses of hematite as large as 1 inch in diameter. Elsewhere within the rock, the light-green calcite and quartz masses occur as small nodules as much as 1 inch in diameter having centers of disseminated hematite. The hornfels that surrounds these bodies displays minute brecciated structures on its margins, possibly the result of shearing stress.

In the paragraphs (p. 32) discussing the structure of the Middle Mountain group, it is suggested that the Mount Mellenthin laccolith is the product of two or more coalescing magmas. It is reasonable to assume that a small body of sedimentary rock caught between and carried upward by these intrusive masses would be subjected to considerable compressional stress, enough to produce the structures described and to effect a higher degree of metamorphism than around the laccoliths.

Sandstone beds in contact with igneous rocks are silicified. On the southwest flank of Mount Peale, sandstone beds of the Salt Wash Member of the Morrison Formation are partly silicified but not enough to be considered quartzite. On Moore's Ridge in the South Mountain area the sandstone beds of the Burro Canyon Formation are considerably silicified. Where these beds abut the stock, silicification has been intense and the rock is a quartzite. Apparently, where permeable sandstone units are cut by igneous rock, especially around the stocks, they served as conduits for the escape of silica-bearing solutions. The Wingate, Navajo, and Entrada Sandstones in this same area are also silicified, but not to the degree observed in the Burro Canyon Formation.

Epidote, as thin films and small crystals, commonly coats the fracture surfaces of igneous rock. Only rarely is epidote found in the sedimentary rocks bordering the igneous rock contact. One place where it is found is on the west side of the sedimentary block included in the top of the Mount Peale bysmalith. The brecciated rock is permeated with epidote that is evenly dispersed through the very fine grained matrix. Epidote imparts a pale green color that is in sharp contrast to the white sandstone fragments comprising the bulk of the breccia. The epidote probably was derived from deuterically altered mafic minerals in the igneous rock.

## AGE

Age determinations based on the lead-uranium ratios of zircons in the three types of porphyry corroborate Waters' (1955) concept of the order of intrusion. Age determinations of zircon from the two types of younger porphyry suggest a Paleocene age for the intrusion of the monzonite porphyry and a Miocene age for the intrusion of the syenite porphyry. Thus the formation of the La Sal Mountains probably spanned Late Cretaceous to early Miocene time, a period of approximately 40 million years. The major part of intrusion, that of the diorite porphyry, probably took place during Late Cretaceous and early Tertiary time, approximately 55 to 65 million years ago.

These conclusions are based on studies of six samples of rocks collected by D. R. Shaw (1957, oral commun.) from the Middle and North Mountains of the La Sal Mountains and submitted to H. W. Jaffe of the U.S. Geological Survey for age determination of the zircon contained. A lead-uranium ratio in zircon method was used and the age determinations obtained are believed to be accurate to $\pm 10$ percent. The zircon from three samples of the diorite porphyry indicates ages of 380, 410, and 470 million years, which approximately correspond to the interval from the Cambrian to the Silurian Period. Zircon from the monzonite porphyry upon which two determinations were made indicates ages of 50 and 53 million years, or about middle Eocene. The zircon from the syenite porphyry indicate an age of 24 million years, or approximately early Miocene.

Hunt and Waters (Hunt, 1958, p. 348–355) have suggested that the original diorite magma was produced by the palingenesis of amphibolite. A continuation of this process at increased temperatures together with attendant filtration differentiation created the monzonite and syenite differentiates. This hypothesis is supported by the age determinations if it is assumed that the older zircon is an unreconstituted fraction of the amphibolite that escaped fusion but which did undergo internal readjustment, and that the younger zircon from the monzonite and syenite porphyries are wholly reconstituted, having crystallized from a higher temperature magma. In addition to an age difference, H. W. Jaffe (written commun., 1957) recognized a physical difference between the zircon of the diorite porphyry and that of the monzonite and syenite porphyries. Zircon crystals in the diorite are elongate, prismatic, and doubly terminated, and those in the monzonite and syenite are short and pyramidal. Jaffe also noted unusually high alpha activity in the zircon of the diorite porphyry. These differences strongly suggest that there was some change in the physical-chemical conditions under which the magma was being generated. Logically this change, as Hunt and Waters indicate, may be due to the increased temperature at which the palingenetic process was carried out in its later stages.

If, as assumed, the zircon of the diorite porphyry is an unreconstituted fraction of the original amphibolite, it poses a serious objection to the Cambrian to Silurian age determination. The amphibolite must have been at great depth if fusion could take place, probably deep within the basement complex. That such rocks are Precambrian in age would be a fair assumption. About

20 miles northeast of the north group of the La Sal Mountains, crystalline basement rocks have been uplifted and are exposed on the Uncompahgre Plateau. A sample of the youngest or nearly youngest granite occurring there showed variation of ages from 1,050 million years to 1,810±160 million years, depending on the mineral analyzed and the method used (Davis, 1954, p. 105). While these differences in ages may be the result of errors in certain basic assumptions regarding the minerals analyzed, they nevertheless imply a Precambrian age for the Uncompahgre granite. The age discrepancy, however, may not be a real one and can be explained in the following way: It is quite probable that zircon in the amphibolitic basement rock became highly metamict before palingenesis. When undergoing the early stages of palingenesis, the zircon was refractory enough to remain unfused but was energized enough to reassume in some degree its original crystallinity and to expel radiogenic lead as it did so. As a result, the lead-uranium age determination was anomalously low, at least 500 million years short of the true age.

Zircon age determinations by Jaffe (written commun., 1957) of the monzonite porphyry indicate that the rock is of Middle Eocene age. The diorite porphyry is intruded by the monzonite porphyry and intrudes the Mancos Shales of Late Cretaceous age; younger sedimentary rocks were either not deposited or have been removed by erosion in the mountain area. Presence of the Mancos limits the emplacement of the great bulk of the igneous rocks of the La Sal Mountains to some time between the Late Cretaceous and middle Eocene.

## STRUCTURAL GEOLOGY

The stratified rocks of the La Sal quadrangle are warped into several gentle folds which, in the northwestern part, have been greatly increased in amplitude by intrusion of laccoliths that make up the La Sal Mountains. Apart from the laccoliths the most conspicuous structural units in the mapped area are the southwestern part of the collapsed Sinbad Valley salt anticline, the northwestern end of the collapsed Paradox Valley salt anticline, and the Pine Ridge salt anticline (pl. 3). In a broader regional picture the Sinbad Valley, Paradox Valley, and Pine Ridge features are but segments of much larger folds: the Sinbad Valley-Fisher Valley anticline, the Paradox Valley-Castle Valley anticline, and the Moab Valley-Pine Ridge anticline. These anticlines trend N. 45° W. to N. 70° W., and are separated by broad, somewhat sinuous and shallow synclinal troughs which, from north to south, include the Roc Creek-Taylor Creek syncline, the La Sal Creek syncline, and the East Coyote Wash syncline. Generally these synclinal troughs plunge gently to the southeast away from the domal uplift of the La Sal Mountains.

In contrast to the regional structural trend, the La Sal Mountains, the highest structural and topographic forms in eastern Utah, form a chain that trends slightly east of north. North Mountain, Middle Mountain, and South Mountain each contain several mountain peaks separated by deeply dissected basins. Most of the basins were formed by glaciation. Structurally, North and South Mountains are similar for they lie within and are elongated parallel to the structural axis of the Paradox Valley-Castle Valley salt anticline and the Moab Valley-Pine Ridge salt anticline, respectively. The igneous intrusions forming these two mountain groups uplifted the entire sequence of strata from the Rico Formation of Pennsylvanian and Permian age to the Mancos Shale of Late Cretaceous age. Middle Mountain, in contrast, is structurally more complex. It is in the intervening syncline and is composed of a stock, dikes, laccoliths, and a bysmalith which selectively intrude the strata at several horizons.

The geologic structure of the area is shown on the geologic map and its accompanying cross sections (pl. 1) and in greater detail on the structural map (pl. 3). Structure contours are drawn on the top of the Entrada Sandstone. Inasmuch as the Entrada is covered by younger sedimentary rocks in many places, the selection of an alternative datum plane was necessary. The base of the Burro Canyon Formation was chosen in preference to other contacts because it shows the least relief on its surface and is exposed widely. These elevations were then projected to the top of the Entrada by subtracting the average thicknesses of the intervening formations.

The cross sections accompanying the geologic map represent an interpretation of the structure along the lines shown and are constructed at the same vertical and horizontal scale.

### FOLDS

#### SINBAD VALLEY ANTICLINE

The Sinbad Valley anticline, part of which is in the northeast corner of the mapped area, trends about N. 45° W. Erosion has removed the crest of the fold and left a valley that is about 9 miles long and 4 miles wide. The valley walls are cliffs and steep slopes having foothills formed by fault blocks composed of Permian, Triassic, and Jurassic sedimentary rocks. Exposed within the valley is a large mass of the Paradox Member of the Hermosa Formation which Shoemaker

(1951) believes is a composite of several distinct salt cells. These cells are outlined by arcuate zones of intricate faulting and, in places, are separated by upturned beds of limestone of the upper member of the Hermosa Formation. Only one of these salt cells is believed to be exposed within the quadrangle boundary.

The southwest flank of the anticline dips from 1° to 8° for 1 mile, to the axis of the Roc Creek syncline. The structural relief between the trough of the Roc Creek syncline and the crest of the Sinbad Valley structure, prior to collapse, is estimated as more than 2,500 feet.

Beyond the mapped area the Sinbad Valley feature is connected on the northwest to the Fisher Valley collapsed anticline by a gentle anticlinal fold and a complex system of faults. Most of these faults form grabens, which are probably the result of loss of salt either by flowage or by solution or possibly both. To the northeast the feature is bounded by the Dolores River syncline which separates it from the Uncompahgre uplift.

#### ROC CREEK SYNCLINE

The axis of the Roc Creek syncline is sinuous, trends generally N. 55° W., and plunges gently to the southeast. It lies between the Sinbad Valley and Paradox Valley anticlines and is separated from the latter by a northwest-trending fault complex known as the Valley View fault. It is, for the most part, an asymmetrical syncline, having steeper dips on the northeast flank. As shown in cross section *A–A′* (pl. 1) the flanks of the syncline are inferred to dip more steeply at depth than at the surface because unconformities truncate the formations near the crests of the adjacent anticlines.

#### TAYLOR CREEK SYNCLINE

The Taylor Creek syncline is a closed synclinal trough bounded on the west by the North Mountain dome and on the southwest and east by faults. Its northern extremity is at the divide between Beaver Basin and the headwaters of Taylor Creek, approximately 6 miles north of the quadrangle boundary. The limbs are nearly symmetrical and dip 30°–45° on the northeast flank and 45° on the southwest flank.

The estimated structural relief from the axis of the Taylor Creek syncline to the crest of the Sinbad Valley anticline before its collapse is more than 4,000 feet. The southwest flank extends to the crest of the North Mountain dome and probably has at least 8,000 feet of structural relief. The presence of the Geyser Creek Fanglomerate, described earlier, within the Taylor Creek syncline indicates that the age of final deformation of the area may have been as recent as late Pliocene or early Pleistocene.

#### CASTLE VALLEY-PARADOX VALLEY ANTICLINE

Only a small part of the Castle Valley-Paradox Valley anticline is within the mapped area, but it is undoubtedly the most interesting and complicated of the structural features mapped, apart from the La Sal Mountains. The major feature, although mainly anticlinal, is, within the mapped area, a composite of several minor folds which have been formed by the uplift and, in places, removal of irregularly shaped salt masses. For descriptive purposes the feature is subdivided into three provinces: the principal valley, Willow Basin syncline, and Scorup anticline.

Paradox Valley, which is 35 miles long and about 5 miles wide, was formed by erosional breaching of a great salt anticline. It is bounded by cliffs and steep slopes formed by sedimentary rocks of Mesozoic age. These strata, ranging from maroon to white, provide some of the most colorful scenery in western Colorado.

Block faulting, landslide debris, and alluvium obscure most of the internal structure of the anticline which Shoemaker (1956a) and Cater (1954a) believe to be composed of clusters of irregularly shaped salt cells situated along the structural axis. An arcuate set of faults in the eastern part of the La Sal quadrangle (pl. 1) suggests that a collapsed salt cell underlies the valley here and near Paradox, Colo.

#### WILLOW BASIN SYNCLINE

The Willow Basin syncline lies northwest of Paradox Valley where Mesozoic formations extend across the valley as a series of steplike cliffs that rise to the northwest. Most of these cliffs were formed by faulting transverse to the synclinal axis. The Willow Basin syncline is bounded on the northeast by the Valley View fault and on the southwest by the Dugway fault. Both are strike faults of considerable local displacement and are described in detail in the section on faults (p. 34). The Dugway fault dies out about 4 miles west of the east boundary of the quadrangle, and beyond it the Willow Basin syncline is flanked by the Canopy Gap anticline.

The Willow Basin syncline is bisected by a transverse fault. The synclinal axis plunges gently southeastward west of the transverse fault, and northwestward east of it. The fold is virtually symmetrical. The limbs dip as much as 12°, except adjacent to the Valley View fault where the beds dip 25° to the southwest. Willow Basin Creek follows a sinuous course along the synclinal axis.

#### SCORUP ANTICLINE

A salt cell probably underlies the Scorup anticline which is between the Geyser Creek and Dead Oak synclines in secs. 11, 12, 13, and 14, T. 27 S., R. 25 E., San Juan County, Utah. The Scorup anticline is asymmetrical and has dips of 23° to 45° on the northeast flank and 8° to 16° on the southwest flank. The structural relief from the crest of the anticline to the axis of the Dead Oak syncline, less than a mile to the northeast, is about 2,000 feet. The southwest limb, from the crest to the axis of the Geyser Creek syncline, has structural relief of slightly less than 1,000 feet. The structural relations along the crest have been obscured by erosion and faulting and covered by alluvium and landslide deposits, but the Scorup anticline apparently has a structural closure of at least 200 feet over an area of approximately 150 acres. Geyser Creek was superimposed on and crosses the anticline at right angles to the axis. It has excavated a deep valley and exposed the sandstone and shale of the Salt Wash Member of the Morrison Formation. The sandstones along the crest of the anticline have dropped between two parallel faults which form a narrow graben that is about 1½ miles long and 500 feet wide. Vertical displacement along the faults ranges from 40 to 80 feet near Geyser Creek and is believed to decrease in magnitude to the northwest and southeast.

#### GEYSER CREEK SYNCLINE

On the southwest side of the North Mountain laccolith is an asymmetrical syncline named for Geyser Creek which originates in Geyser Pass, the divide between North and Middle Mountains. The axis of the Geyser Creek syncline plunges gently eastward from the pass and swings southeastward where it closes in a narrow, shallow basin in the SE cor., sec. 10, T. 27 S., R. 25 E., San Juan County, Utah. From that point the plunge is reversed and the structure extends southeastward for about 1 mile where it gradually fades out against a minor anticlinal cross fold that separates it from the Willow Basin syncline.

The northeast limb dips from 45° to nearly vertical. The structural relief from the trough of the Geyser Creek syncline to the crest of the North Mountain anticline, less than 2 miles away, is more than 4,700 feet. The southwest limb dips 15° to 25° NE. and has an estimated 3,000 feet of structural relief from the trough of the syncline to the crest of the Middle Mountain dome, more than 4 miles to the south. The relations of the Geyser Creek syncline to the adjacent structural features are considered in more detail in the discussion of Middle Mountain (p. 30).

#### LA SAL CREEK SYNCLINE

The La Sal Creek syncline plunges southeastward across the central part of the mapped area from La Sal Pass, between Middle and South Mountains, to the Dolores River, southeast of the map boundary. It is bounded on the northeast by the Canopy Gap anticline and the Dugway fault, both resultant features of the collapse of the Paradox Valley anticline. On the southwest it is bounded by the South Mountain dome and the Pine Ridge collapsed anticline. The syncline is named for La Sal Creek which parallels and, in places, flows along the sinuous trend of the structural axis for 20 miles.

The limbs of the syncline are asymmetrical, having different inclinations on the northeast and southwest depending on the location and magnitude of the adjacent folds. For example, near the Paradox Valley anticline the northeast limb dips 8° to 10° SW., and the southwest limb dips 1° to 3° NE., toward the synclinal axis. Along Moore's Ridge of South Mountain, however, the southwest limb dips 40° to 50° NE., and the northeast limb dips as much as 10° SW., except where disturbed by the intrusive rocks of Middle Mountain. The La Sal Creek syncline appears to have been subjected to differential stresses that were both compressional and torsional. The torsional forces were probably quite small in proportion to the large area involved, but such forces may explain the diverse joint patterns in the La Sal Creek area which are discussed with faults and joints (p. 34).

Structural relief from the axis of the syncline to the axis of the Paradox Valley anticline is estimated to be at least 1,500 feet, in sharp contrast to the relief of the southwest limb which is about 200 feet on Wray Mesa. Near La Sal Pass the structural relief from the syncline axis to the crest of the Middle Mountain dome is 2,900 feet, whereas the relief of the southern limb, that is, to the eroded crest of the South Mountain dome, is estimated to be about 5,100 feet.

#### PINE RIDGE ANTICLINE

South of the La Sal Creek syncline is a gentle anticlinal arch that is a continuation of the Gypsum Valley anticline to the south and the Moab Valley anticline northwest of the mapped area. The arch has been subdivided into the Pine Ridge anticline, which is in part collapsed, and the South Mountain dome. The South Mountain dome is discussed on page 33.

The Pine Ridge anticline is a broad, somewhat asymmetrical structure. The northeast limb dips 1° to 2° NE. toward the axis of the La Sal Creek syncline 2.5 miles distant. The southwest limb dips as much as 5° and extends from the crest of the anticline to the axis of the East Coyote syncline, 4.5 miles to the southwest.

Mapping and study of the structural features of the Pine Ridge anticline suggest that the area is underlain by a buried salt mass. The presence of this mass has been confirmed by gravity surveys made in 1957 by the U.S. Geological Survey. This was further confirmed in 1963 (R. J. Hite, oral commun.) when the Tenneco well Redd Ranch No. 1 in the SE¼NE¼SW½ of sec. 28, T. 28 S., R. 25 E. cut important potash mineralization in Paradox salt between 3,300 and 3,510 feet in depth. The gravity survey (Byerly and Joesting, 1959, p. 48–49) indicates that the center of the broad open valley of Old La Sal extending from the head of La Sal Creek Canyon to South Mountain is underlain by an elongate salt intrusion. The strata overlying the plug have been downdropped at least 300 feet, probably as a result of dissolution of the salt. The collapse area is bounded by Pine Ridge on the south, southwest, and southeast and by another low ridge on the northeast that parallels La Sal Creek. Surficial material obscures the structural features in the north and central parts of the valley. Landslide and slump features that occurred after collapse border the southern margin of the valley. Gravity measurements on Wray Mesa, to the southeast of the collapse area, indicate that there the Pine Ridge anticline is underlain by little or no salt and owes its existence solely to regional tectonism.

#### EAST COYOTE WASH SYNCLINE

A part of East Coyote Wash syncline lies in the southwest corner of the mapped area and separates the South Mountain dome and Pine Ridge anticline from the Lisbon Valley anticline. In the mapped area the limbs strike about N. 70° W. and N. 50° W., are virtually symmetrical, and have dips as high as 5°. The whole syncline is an elongate closed trough that is 13 miles long and about 6 miles wide. The amount of closure is about 600 feet. The lowest part of the trough is at the head of Greasewood Canyon in the northern part of the Lisbon Valley quadrangle about 4 miles south of the mapped area. Northwest of the trough is the West Coyote Wash syncline which is separated from East Coyote Wash syncline by closure of low relief and marked by a gentle drainage divide about 1 mile west of the map boundary. The southeastern end of the East Coyote Wash structure closes at Island Mesa where a gentle arch separates it from Disappointment syncline in Montrose County, Colo.

The rocks exposed within that part of the East Coyote Wash syncline that lies within the mapped area are dominantly the Dakota and Burro Canyon Formations of Cretaceous age. Much of the Dakota has been removed by erosion, and near the synclinal axis widespread deposits of alluvium obscure the contacts. Fragments of marine fossils and Mancos Shale that probably had been moved but a short distance were noted in sec. 25, T. 28 S., R. 24 E., northeast of the village of La Sal, but no Mancos was found in place in the vicinity of East Coyote Wash. To the east and north of East Coyote Wash, deep canyons have been cut by streams draining the southwest flank of the Pine Ridge anticline. These streams flow southward into East Coyote Wash and in many places have eroded the Cretaceous caprock and exposed the Brushy Basin Member of the Morrison Formation.

#### LA SAL MOUNTAINS

The La Sal Mountains comprise three distinct structural units (Hunt, 1958). All are virtually laccolithic but the configuration of North Mountain and South Mountain contrasts with that of Middle Mountain. The difference is due to the presence of preexisting geologic structures that controlled in a large degree the emplacement of the mountain-building magma. A great part of the igneous rock forming North and South Mountains was emplaced along an incompetent horizon or zone at the top of the salt that forms the cores of the salt anticlines. The igneous cores are composed of many tonguelike laccoliths that extend from a central stock and are emplaced mainly along the trend of the anticlines, where they form elongate domes. The entire sedimentary sequence overlying the salt-bearing Hermosa Formation has been uplifted along the margin of the intrusive rocks. Middle Mountain, in contrast, is in a synclinal area between the anticlines where little if any salt remains. Lacking an incompetent zone at depth, the magma moved farther upward into younger formations where several laccoliths and a bysmalith formed at or in at least three different horizons or zones. These igneous rocks intrude and are surrounded by sedimentary rocks of Jurassic and Cretaceous age, and are connected to a central stock by small dikes and apophyses.

#### NORTH MOUNTAIN

North Mountain has been studied in considerable detail by Hunt (1958). Only a small part of it extends into the northern edge of the area included in this report. The igneous core was emplaced directly in the trend of the Castle Valley-Paradox Valley anticline and is elongate parallel to this trend. All sedimentary formations down to and including part of the Hermosa Formation of Pennsylvanian age have been uplifted on both sides of the mountain to form a large elongate dome which plunges sharply to the southeast within the north boundary of the mapped area. The crest of the dome has been eroded away exposing an igneous core of diorite porphyry which crops out as sharp peaks and ridges that form the walls of deeply dissected valleys.

Haystack Mountain and Mount Tomasaki at the southern end of North Mountain lie within the La Sal quadrangle. Mount Tomasaki is bounded on the south by Porcupine Ridge which consists of sedimentary rocks that were upturned by igneous intrusion.

The limbs of the North Mountain anticline dip from 45° to 90° and in places may be slightly overturned. In most places the folding is symmetrical. Vertical and overturned bedding appear to be localized near intrusives which lie outside the main igneous mass. This bedding was observed on Porcupine Ridge at Haystack Mountain and near intrusives in the drainages of Bear and Beaver Creeks north of the mapped area.

Hunt (1958, p. 322) described Haystack Mountain as a laccolith resting on Mancos Shale from outcrops in Burro Pass immediately north of the La Sal quadrangle boundary. The authors traced this contact from Burro Pass around the southeast margin of the intrusive and found it bordered by vertical sandstone and mudstone units of the Morrison, Burro Canyon, and Dakota Formations. The absence of older strata suggests that Haystack Mountain may be either a vertical plug or a laccolith emplaced along incompetent beds of the Morrison Formation.

Nowhere within the quadrangle is the base of the igneous core of North Mountain or Haystack Mountain exposed. The authors agree with Gould (1926, p. 91) that the horizon of intrusion is probably directly below that represented by the stratification contacts found around them. Rocks along the igneous contact may not be everywhere of the same formation. Within the mapped area, float from the sedimentary rock in contact with igneous rock of Mount Tomasaki is dominantly limestone and may belong to the Hermosa Formation. Presence of this horizon along the margin of intrusive rock would better explain the presence of isolated outcrops of the Hermosa which Hunt and Waters (Hunt, 1958) found in Beaver and Miners Basins, well within the boundaries of the main igneous mass.

#### MIDDLE MOUNTAIN

The group of peaks comprising the central part of the La Sal Mountains were referred to as Middle Mountain by Hunt (1958). Although complex in detail, Middle Mountain is, in general, formed by a domal uplift within a syncline lying between the Castle Valley-Paradox Valley anticline and the Spanish Valley-Pine Ridge anticline (pl. 3). The center of the dome is at the head of Gold Basin between Mount Peale and the west edge of the mapped area in secs. 14 and 23, T. 27 S., R. 24 E., San Juan County, Utah. Sedimentary rocks dip away from the crest of the dome at angles from 10° to 42°.

The intrusive rocks of Middle Mountain are composed almost entirely of diorite prophyry and crop out as a stock, as dikes, sills, laccoliths, and as a bysmalith that were apparently intruded in that order.

#### STOCK

The stock is an irregularly shaped mass of igneous rock near the center of domal uplift, and is distinguished from the other igneous bodies by its smaller size, irregular shape, and crosscutting relationship with the surrounding country rock. The stock exposed in Middle Mountain is less than 3,000 feet long and less than 1,500 feet wide, but is considerably larger than the associated dikes. It may extend under the covering rock debris as one continuous igneous mass that also forms Mount Tukuhnikivatz, just west of the map boundary.

The outer margins of the stock are nearly vertical and crosscut the sedimentary formations at sharp angles. Where exposed, the contact of igneous and sedimentary rocks is well defined. The stock is surrounded for the most part by a shatter zone in which the adjacent sedimentary rocks have been indurated and darkened by mild metomorphism. Minor deposits of copper and iron occur in the stock and the adjacent sedimentary rocks. The surrounding laccoliths and related intrusions appear to have been injected radially along feeder dikes from the stock. The close association of the stock and dikes can best be observed in the glacial cirques in sec. 14 and the S½ sec. 11, T. 27 S., R. 26 E.

#### DIKES

Most of the igneous dikes cross the sedimentary contacts at right angles, but some are inclined at steep angles to the bedding. Those in sec. 14 and the S½ sec. 11, T. 27 S., R. 26 E., tend to crop out in a radial pattern from the parent stock. This characteristic was of considerable aid in determining the types of igneous bodies that were being mapped in areas where landslide and talus obscure the contacts. The dikes range in width from a few feet to about 200 feet and are exposed for distances of as much as 1,000 feet. Most appear to have formed along fault planes where the vertical displacement of the adjacent formations is usually less than 100 feet. These dike-filled faults were formed during the intrusion of the central stock and initial uplift of the Middle Mountain dome.

Associated with this dike swarm are a clastic dike and a clastic pipe which occur near the west boundary of the quadrangle, southwest of Mount Mellenthin and northwest of Mount Peale, on the ridge separating Gold Basin and Dorry Canyon in sec. 14, T. 27 S., R. 24 E., San Juan County, Utah (pl. 1).

The clastic dike is about 1,300 feet long and bears approximately N. 30° E., across the ridge line separating the two basins. The dike is partly obscured over most of its length by a thin cover of talus, but is well exposed at the crest of the ridge where it is about 55 feet thick. The dike is vertical and emplaced along a fault over most of its length. It diverges from the fault at the southwest end. The dike extends beyond the fault at the northeast end, or at least beyond the point of any apparent throw. No vertical offset was seen in the transected beds on the Dorry Basin side of the ridge.

The dike is dark gray with a greenish cast and is composed of bleached fragments of shale, siltstone, sandstone, and limestone (fig. 5). The fragments range from sand size to 3 feet in diameter and are angular to well rounded. They are highly indurated, much more so than either the rocks from which they were derived or the beds adjacent to the dike wall.

The matrix, observed in thin sections, is composed of tightly packed, rounded to angular quartz grains and minor amounts of calcite which fills the interstices. In places, abundant amounts of very fine grained black opaque magnetite(?) are embedded in the calcite. A very minor amount of plagioclase with albite twinning

FIGURE 5.—Outcrop of clastic dike exposed in copper prospect in the NW¼ sec. 14, T. 27 S., R. 24 E., San Juan County, Utah. Photograph shows angular to round boulders of siltstone, sandstone, and limestone in a matrix of squeezed and folded gray-green shale. All appear to have been derived from the Mancos Shale and dropped downward into the Morrison Formation which comprises the surrounding wallrock.

was noted in one section; some of it appears to be highly sericitized.

The fact that most of the quartz grains display undulatory extinction suggests strain. Some of the grains are fragmented, although optically they appear as whole units; none of the fragmented parts have been displaced relative to the others. Haff (1944, p. 213–214) notes this same peculiarity in two clastic dikes near Placerville, Colo., and believes such structure could have been formed only in place because a shattered fragment would disintegrate when moved.

At its northeast end the dike cuts through the Dakota and Burro Canyon Formations into the upper part of the Brushy Basin beds; at its southwest extremity it cuts almost to the base of the Brushy Basin. Where well exposed at the ridgecrest, the dike contains fragments derived from the Entrada or Navajo Formation and younger Jurassic formations. No fragments of the Kayenta Formation and older formations were recognized. These fragments are adjacent to undisturbed beds of the Dakota Sandstone. Fossiliferous fragments of the Mancos Shale that have moved downward in the structure were noted adjacent to the Dakota Sandstone. At the southwest end of the dike, where it is exposed for a width of 10 to 15 feet, the clastics are composed of rounded fragments of indurated shale and some limestone derived from the Mancos Shale. The matrix is composed of comminuted shale that contains sparse copper minerals, mostly malachite. It appears, therefore, that the Mancos Shale fragments have moved downward through the Dakota, Burro Canyon, and most of the Brushy Basin, a vertical distance of about 500 feet.

The clastic pipe, too small to be shown at the map scale, is in NW¼ sec. 14, T. 27 S., R. 24 E., about 1,000 feet northwest of the clastic dike and about 200 feet below the ridge top. It is roughly oval in plan and is about 40 feet wide and 80 feet long. It crops out 80 feet above the base of the Brushy Basin Member of the Morrison Formation, but structural relations with the surrounding bed rock are mostly obscured by rubble.

The pipe is composed of angular to subrounded fragments of sandstone and mudstone that range from sand size to 4 inches in diameter and are derived from the Morrison, Summerville, and Entrada or Navajo Formations. No fragments from other formations were recognized.

The matrix consists predominantly of quartz and very sparse amounts of feldspar and calcite. The quartz commonly occurs as shattered grains, but in places it is found as aggregates of anhedral grains. These grains are conspicuous in contrast to the rest of the matrix because they are larger and unshattered; they may be of hydrothermal origin. The feldspar is oligoclase and is highly sericitized. Calcite fills the interstices of the shattered quartz grains of the matrix, but in some places it occurs as euhedral rhombs. Both the feldspar and calcite may have been introduced by solutions.

#### SILLS

Closely associated with the stock and dikes are several small sills which have been selectively injected into less competent beds. The sills are projections of diorite porphyry that extend from the stock or dikes along incompetent bedding planes and are, therefore, concordant with the country rock. These extensions are usually less than 500 feet long and less than 100 feet thick.

One sill, in sec. 23, T. 27 S., R. 24 E., San Juan County, Utah, extends from the Middle Mountain stock into the mudstone beds of the Salt Wash Member of the Morrison Formation near the contact with the Brushy Basin Member. A second sill, on the southwest side of Mount Mellenthin in the NE¼ sec. 14, T. 27 S., R. 24 E., is at the top of a vertical dike and extends along the contact between the Dakota Sandstone and Mancos Shale approximately 300 feet. A minor fault at the distal end of the sill uplifts the beds above the igneous body. A third sill was observed near La Sal Creek east of La Sal Pass. It is intruded along strata in the Mancos Shale and appears to be derived from the igneous core of South Mountain. Unfortunately much of the intervening area is covered by thick glacial deposits and the relationship is not exposed.

#### LACCOLITHS

Like the sills, the laccoliths are generally in concordant contact with the surrounding country rock and have been preferentially injected into some of the less competent formations or along the less coherent horizons. The most common horizons of injection recorded in the mapped area are the Mancos Shale, the top of the Kayenta Formation, and the top of the Hermosa Formation. There may be an inverse relationship between the horizon of intrusion and the order in which the igneous bodies were emplaced, that is, the igneous bodies found in the Mancos may have been injected prior to those found in the Kayenta or Hermosa Formations and similarly those in the Kayenta prior to those in the Hermosa.

##### MOUNT MELLENTHIN

The most clearly exposed laccolith of Middle Mountain in the mapped area is that of Mount Mellenthin which rests concordantly on the Mancos Shale about 400 feet above the contact with the Dakota Sandstone. The horizon of intrusion is within a fissile shale that rests on a sequence of calcareous siltstone and silty limestone beds. The sedimentary rocks that formerly covered the laccolith have been entirely removed by erosion. The exposed igneous core is 1,350 feet thick and covers a roughly circular area about 4,000 feet in diameter. The laccolith appears to have been fed by a group of dikes that radiate from the stock which lies to the southwest. A thin, dikelike projection of Mancos Shale extends from the base of the laccolith to the crest of the mountain. The beds have been upturned and compressed by the surrounding igneous rock. This deformation may indicate that the Mount Mellenthin laccolith was formed by several smaller but distinct lobes which coalesced as intrusion progressed. Such a process may explain other such "inclusions" associated with the laccoliths.

An arcuate fault on the south and east flanks of Mount Mellenthin separates the laccolith from neighboring intrusive masses. The sedimentary rocks near the mountain are downthrown as much as 500 feet. The upthrown side of the fault is probably underlain by a buried laccolith which extends away from the fault in a northeasterly direction and forms the core of the Blue Lake anticline. The major part of the igneous core is covered. The horizon of injection is believed to have been along the contact between the Navajo and Kayenta Formations, as in Mount Peale to the south. A small part of the magma appears to have moved upward along the fault and into the Morrison Formation to form the diorite porphyry in the center of sec. 12, T. 27 S., R. 24 E., San Juan County, Utah.

A similar buried laccolith projects eastward from Mount Peale in secs. 19, 20, and 21, T. 27 S., R. 25 E. It is overlain by the Entrada Sandstone and younger sedimentary rocks exposed in the headwaters of Twomile Creek, and may be connected to the Mount Peale intrusive mass. The horizon of intrusion is also thought to be along the Navajo-Kayenta contact. The beds folded over the laccolith form the Twomile anticline. The distal end of the buried laccolith is about 2 miles east of Mount Peale, where the anticline plunges abruptly.

#### BYSMALITH

##### MOUNT PEALE

The Mount Peale bysmalith lies south of Mount Mellenthin and the arcuate fault mentioned in the preceding paragraphs. Iddings (1898) suggested the term "bysmalith" for intrusions, the roofs of which have been uplifted by faulting. Hunt (1953, p. 108) noted in the Henry Mountains that the linear bulge or anticlinal appearance of the laccolith was in contrast with the bysmalith which he described as a circular bulge surrounded by quaquaversal dips. Hunt further states that the bysmaliths of the Henry Mountains were distinguished from stocks and laccoliths by (1) very steep contacts which have been ruptured on the side of the bysmalith away from the parent stock, and (2) the fact that the contacts near the stock are raised by folding; however, like that of the laccolith, the roof of the bysmalith is less displaced on the side toward the stock than on the distal side.

Most of these features can be observed on Mount Peale, for it is a circular bulge of igneous rock capped by an isolated block of sedimentary rocks that is more than 600 feet thick. These rocks include the lower part of the Brushy Basin Member and the Salt Wash Member of the Morrison Formation, the Summerville Formation, the Entrada Sandstone, and possibly the Navajo Sandstone. The Navajo Sandstone is probably present, although most of Mount Peale is covered with a thin mantle of rock debris. Fragments of sandstone very similar to the Navajo were found on the east face in the talus below large blocks of Entrada and above the igneous rock debris. Within the sedimentary cap is a thin, continuous limestone bed, 1 to 4 feet thick, that strikes N. 25° W. and dips 17° SW. and marks the base of the Salt Wash Member of the Morrison. This distinctive bed was of considerable aid in determining the formations present in an area that is mostly covered by talus. The limestone bed can be traced around the peak of Mount Peale on three sides, but on the fourth, the southwest side, the beds are truncated by a vertical wall of igneous rock which is part of the bysmalith. Similar truncation of the Summerville and older formations can also be observed on the northeast end of the peak. The distribution of rock types represented in the talus covering Mount Peale indicates that the sedimentary rock cap is completely underlain by igneous rock. The cap has been raised at least 3,000 feet above the corresponding stratigraphic contacts of the surrounding sedimentary rocks.

The lack of quaquaversal dips of the beds surrounding Mount Peale indicates partial nonconformity with the criteria established by Hunt (1953, p. 109) which define the bysmaliths of the Henry Mountains. On the south and southeast the beds dip away from the mountain at angles as high as 45°. On the north, however, they dip eastward at more gentle angles of no more than 19° and the beds appear to have been ruptured by the igneous mass which crops out as a vertical cliff 400 feet high. Structural relationships indicate that the area included in the Dark Canyon cirque may be underlain by a laccolithic lobe connected to the Mount Peale intrusive and injected along the Navajo-Kayenta contact as far north as the arcuate fault south of Mount Mellenthin. The intrusion of this laccolith and that underlying the Blue Lake area have raised the overlying strata south and east of the fault. The fault indicates that these intrusive masses may have formed contemporaneously but were formed later than the Mount Mellenthin laccolith. East of Mount Peale the beds have been folded by the Twomile Creek laccolith, but in general dip eastward. To the west the beds dip southward reflecting more the irregular nature of the contact on that side of the bysmalith.

The structural relations displayed in Middle Mountain suggest that the stock domed and intruded the strata, filling the resultant faults and joints with viscous magma which moved upward and outward from the stock until it reached the Mancos Shale, the least competent formation in the stratigraphic sequence. There the magma moved laterally along bedding planes and formed a sill. As the sill cooled and crystallized, it was domed gently upward by continuous magmatic injection until it formed the Mount Mellenthin laccolith. At this point there may have been a minor cessation of intrusion which allowed the magma to cool and crystallize at depths below the Morrison Formation. Such a process might explain the paucity of laccoliths in the Morrison of the La Sal, in contrast to the relative abundance of laccoliths intruding the Morrison of the Henry Mountains. Whatever the cause may have been, the Navajo-Kayenta contact, rather than the Morrison Formation, was intruded at Mount Peale and in Dark Canyon. Injection along this contact probably started as a sill. As the body slowly cooled and crystallized, continuous injection expanded, raised, and eventually ruptured the overlying beds, which were lifted well above the surrounding area to form the bysmalith of Mount Peale. As conduits became clogged or as the weight of the igneous rocks and overlying beds became equal to the upward force of intrusion, the magma moved laterally and formed the adjacent laccolithic lobes under the Dark Canyon cirque and at the head of Twomile Creek. The Blue Lake laccolith probably formed at this time but may have been fed by a separate dike. These laccoliths uplifted the overlying beds and ruptured them along the arcuate fault that marks the margin of the stable area created by the Mellenthin laccolith.

### SOUTH MOUNTAIN

Northwest of the Pine Ridge anticline and lying within the same structural trend is South Mountain, a laccolithic intrusion much like North Mountain. The igneous core of the mountain is exposed within the crest of an eroded dome. The core is composed of diorite porphyry and extends as laccolithic lobes from a large central stock that is just west of the mapped area.

Flanking the laccoliths of South Mountain is a sequence of sedimentary rocks of late Paleozoic and Mesozoic age. The contact between the igneous and sedimentary rocks is not as well exposed as in North Mountain, owing to mass wasting by erosion and cover by thick deposits of talus. Where exposed, the diorite porphyry is in contact with yellowish-brown to dark-gray petroliferous limestone thought to be part of the Rico or Hermosa Formation. The horizon of magmatic injection, therefore, is considered to be the same as in North Mountain.

Moores Ridge, a hogback of Jurassic sandstone, flanks the northeast side of the igneous mass. Near the base, along La Sal Creek, the Burro Canyon and Dakota Formations crop out as pointed, flatironlike hogbacks. These strata trend N. 40°–80° W. and dip 35°–50° NE. A thin sill of igneous rock is exposed in the Mancos Shale in secs. 35 and 36, T. 27 S., R. 24 E. This sill is connected to the central stock of South Mountain, but most of it is obscured by glacial and landslide debris. Hunt and Waters (Hunt, 1958) mapped the outcrop as a tonguelike sill projecting from a small laccolith lying west of the mapped boundary and north of the stock.

South of the mountain the sedimentary rocks have been beveled by erosion and covered by thick deposits of unconsolidated fan gravel. A prominent hogback, similar to Moores Ridge, lies along the structural trend west of the mapped area. In sec. 23, T. 28 S., R. 24 E., south of Coyote spring is a small area where the fan gravels have been removed and the more resistant units of the formations of Mesozoic age have been exposed. The oldest rocks exposed there are thought to be of Permian age. The youngest exposed rocks belong to the Burro Canyon Formation of Cretaceous age. The younger beds dip to the southwest at an angle of 70°, whereas the older beds are known to be inclined only about 55° and may be inclined as little as 35°. Measurements of formational thicknesses indicate that a relatively normal stratigraphic sequence is represented. Inasmuch as no faults were found to explain them, the differences in dip are believed to represent a flexure caused by a minor bulge in the wall of the laccolith.

## FAULTS

### GENERAL FEATURES

Longitudinal, transverse, and radial faults have been mapped in the La Sal quadrangle. Most are high-angle to vertical faults having normal dip-slip movement resulting from deformation by tensional forces involved in the uplift or collapse of salt anticlines or the intrusion of the igneous rocks of the La Sal Mountains. Displacements are from a few feet to a few thousand feet. The greatest displacement is along longitudinal faults that extend along the flanks of the collapsed anticlines and can be traced for 5 miles or more (pl. 3). The collapsed anticlines are transected by many cross faults that are commonly of lesser magnitude and linear extent. A few radial faults are associated with the domal uplift of Middle Mountain. One of the longer faults, a longitudinal fault that parallels the regional trend, may be rotational, that is, the beds on the upthrown side at one end of the fault are downthrown at the other end. In tracing such a fault from one end to the other, it is observed that the vertical displacement decreases in magnitude until an area is reached where there is virtually no displacement.

Major deformational stress was mostly tensional, and there were two periods of rupture resulting from two types of movement. The first and most important was the uplift and rupture of the sedimentary rocks by the formation of salt anticlines and, later, igneous domes. Between some of the centers of uplift, minor torsional forces may have been introduced. The second period of deformation involved the collapse of the strata, owing to removal of the underlying salt masses. This removal was by solution of the salt, or by adjustment of the salt to the lithostatic load, or by a combination of both processes. Much of the original displacement resulting from uplift has undoubtedly been masked by later collapse.

### LONGITUDINAL FAULTS

#### VALLEY VIEW FAULT

The Valley View fault is a vertical fault which trends northwest across the northeast corner of the mapped area. It separates the Roc Creek syncline on the northeast from the Willow Basin and Taylor Creek synclines on the southwest. It can be traced beyond the east boundary of the mapped area for about 1 mile into the adjacent Roc Creek quadrangle to where it is obscured by the alluvium of Paradox Valley. To the northwest it extends 1 mile beyond the mapped area where it merges with a monoclinal fold on the southwest flank of the Sinbad Valley anticline. Along Carpenter Ridge, branch faults extend in a more westerly direction and probably pass under Pine Flat and across Geyser Creek before dying out. The branch faults separate the Willow Basin and Taylor Creek synclines.

Along the fault near the Valley View mine, from which the fault is named, beds on the southwest side have been upthrown an estimated 990 feet. Erosion has exposed the Wingate Sandstone, which dips as much as 42° SW. and crops out as a prominent knifelike ridge at the head of Paradox Valley. At the mine the Wingate is in contact with the middle of the Morrison Formation. The uppermost sandstone of the Salt Wash Member of the Morrison has been dragged upward into a nearly vertical position, and it is this upturned block that contains the uranium deposits of the Valley View mine.

Near Buckeye Reservoir the main fault is joined on the southwest by a group of less conspicuous faults that form a complex zone which is a horst that has a maximum width of 2,000 feet. Blocks of sedimentary rocks within the zone have been uplifted and dip 33°–70° NE. North of this area the fault bordering the southwest side of the horst may swing westward under the alluvium of Pine Flat and join a subsidiary fault which separates the Taylor Creek syncline from the structures southwest of it. In the Willow Basin and Taylor Creek synclines, thick alluvial deposits cover most of these features.

The Valley View fault may be rotational. At the northwest end of Carpenter Ridge, sec. 8, T. 27 S., R. 26 E., the structural relations are obscured by landslide debris composed entirely of Burro Canyon Sandstone. A small outcrop of Burro Canyon Sandstone southwest of the fault plane suggests that there has been very little if any displacement, and that the debris may cover the fracture zone near the axis of rotation. Northwest of Carpenter Ridge, the direction of throw along the fault is reversed; downthrow of the beds is on the southwest. Maximum displacement along this part of the fault is estimated to be 120–170 feet. Faulting is marked by displacement of contacts and opposed attitude of beds on either side of the structure at the junction of Geyser and Roc Creeks. Beds within the Roc Creek syncline dip from nearly horizontal to 12° NE., and across the fault the beds on the flank of the Taylor Creek syncline dip 22°–45° SW.

Apparent rotation along the fault, and other evidence, suggests that deformation of the Valley View fault took place at different times in different places as a result of different causes. Rupture probably began near the Valley View mine in the final stage of salt uplift during formation of the Paradox anticline. Uplift of the Sinbad Valley anticline and initial formation of the Taylor Creek and Roc Creek synclines were probably concurrent. Rupture at the northwest end of the Valley View fault took place somewhat later as preglacial erosion of North Mountain deposited thick layers of sand, gravel, and boulders in the basin formed by the Taylor Creek syncline. These deposits increased the lithostatic load of the basin and caused it to deepen and rupture along its eastern margin.

###### DUGWAY FAULT

The Dugway fault is a longitudinal fault on the southwest flank of and parallel to the axis of the Paradox anticline. It trends N. 55° W. and 4 miles within the quadrangle boundary, and extends southeastward almost to Bedrock, Colo. It is part of an intricate system of faults resulting from collapse along the valley margin. At the northwest end it dies out on the nose of the Canopy Gap anticline which formed as the Paradox Valley anticline collapsed and formed the Willow Basin syncline. Nowhere is there any evidence that the fault was caused by the uplift of the evaporite intrusives; it is therefore thought to be solely the product of collapse. Where exposed, the beds along the fault scarp have been downthrown toward the valley from 300 to 460 feet. The displacement of the fault decreases along its strike to the northwest. Additional step faulting parallel to the Dugway fault immediately east of the mapped area indicates that some blocks along the margin of the valley floor may have dropped 1,500 feet or more.

###### GEYSER CREEK FAULTS

Several minor faults have been mapped in the general area of Geyser Creek in the north-central part of the quadrangle. Some are longitudinal and others are transverse to the Geyser Creek syncline, the Scorup anticline, and the Dead Oak syncline—minor folds at the northwest end of the Willow Basin syncline. These folds are thought to have formed over a salt cell from which salt was later removed. The faults are thought to reflect incipient collapse of the beds overlying the cell. The Scorup anticline is breached by two parallel normal faults of 40 to 80 feet of throw which form the margins of a small graben. The faults join to the southeast to form a single fault that dies out about 1.5 miles to the southeast.

Two faults cut the Dead Oak and Geyser Creek synclines at oblique angles to the graben. The fault cutting the Dead Oak syncline is best exposed on the southern flank of that structure where the contact of the Burro Canyon and Dakota Formations is displaced about 20 feet, with the east side down. The fault was not found to cross Geyser Creek and is therefore not believed to abut the graben faults.

The fault cutting the Geyser Creek syncline is well exposed in the NW¼ sec. 14 where sandstone of the Burro Canyon Formation is downthrown 40 feet on the south side of the fault. Farther west the fault is covered with sandstone debris, but a good exposure in the NE¼ sec. 15 shows the Burro Canyon and Dakota Formations to be upthrown on the south side of the fault. This displacement suggests that rotational movement has taken place along the fault plane probably as a result of differential subsidence over the salt cell. The beds on the south side of the fault at the west end have moved down less than those on the north, whereas to the east they have moved down more.

777-039 O—65——6

Two minor normal faults lie midway between the axes of the Geyser Creek syncline and the Canopy Gap anticline. They are in the extension of the Willow Basin collapse area and may mark the margin of an underlying salt plug.

An unnamed longitudinal fault lies about half a mile south of the Buckeye sawmill and may extend northwestward under Pine Flat. The fault cuts the southeast extension of the Scorup anticline and separates it from westward-dipping beds northeast of the fault that were tilted by movement along the Valley View fault.

### TRANSVERSE FAULTS

#### PARADOX VALLEY

The faults at the north end of Paradox Valley, with the exception of the Valley View fault, are discussed here as a group because of their intimate relationship and common origin. An arcuate fault zone represented by four curved fault traces in sec. 31, T. 48 N., R. 19 W., lie just west of the village of Paradox, Colo. (pl. 1). The faults bound the northwestern margin of an inferred salt cell, one of many that formed the Paradox anticline. The two small mesas just east of the faults are capped by the Kayenta Formation. They are separated by two east-trending parallel faults between which the Entrada and Navajo Sandstones are exposed. This graben may represent the center of the collapsed salt dome.

Some of the marginal faults extend northeast from the arcuate zone across the northwest end of Paradox Valley and are represented by a series of steplike cliffs, the most prominent of which is marked by outcrops of Entrada Sandstone. These faults are nearly at right angles to the axis of the Paradox anticline and probably are the result of the collapse. A similar fault crosses the Willow Basin syncline about one-half mile below the confluence of Buckeye and Mellenthin Creeks at West Paradox Creek. There the Burro Canyon and Dakota Formations are downthrown more than 250 feet on the southeast side. The displacement decreases toward both extremities of the fault. The northeast end appears to die out near the Burro Canyon escarpment in sec. 13, T. 48 N., R. 20 W., Montrose County, Colo., but it may extend to the Valley View fault. The southwest end may terminate about 1,500 feet short of the Dugway fault.

Two minor longitudinal faults are on the southwest flank of the Willow Basin syncline, mainly in sec. 25, T. 48 N., R. 20 W., where they abut the transverse fault that cuts the Willow Basin syncline. Their southeastward extent is not accurately known. They roughly parallel the structure of the syncline and are thought to be the result of local subsidence in the area between the synclinal axis and the Dugway fault. Their formation may have been concurrent with or later than the transverse fault.

#### SHARP CANYON FAULT

A small part of the Sharp Canyon fault is exposed in the south fork of Sharp Canyon in secs. 19 and 30, T. 47 N., R. 19 W., Montrose County, Colo. The fault trace is marked by a zone of silicified veinlets in the Entrada and Navajo Formations exposed in the floor and walls of the canyon. The fault bears N. 22° E. and extends into the adjacent Paradox quadrangle where it curves eastward toward the margin of Paradox Valley. Near La Sal Creek the beds are downthrown on the southeast and have an average throw of 30 feet. This displacement continues southwestward to Wray Mesa where the fault becomes difficult to trace in the shale beds and highly lenticular sandstone of the Salt Wash Member of the Morrison Formation.

The fault is transverse to the regional trend of the folds with which it is associated. It is approximately parallel to and is similar in displacement and other respects to the Cashin fault to the southeast beyond the limits of the map. The economic possibilities of the Sharp Canyon fault are discussed on page 76.

### RADIAL FAULTS

#### MIDDLE MOUNTAIN

The radial faults of the Middle Mountain dome contrast with the longitudinal and transverse faults. The majority are associated with and radial to the intrusive stock in the west-central part of the mountain group. In the structural formation of Middle Mountain there appears to have been at least two periods of igneous intrusion and major faulting and possibly a third period of minor faulting. The first period accompanied the intrusion of the central stock and resulted in the formation of faults that are more or less radial in pattern. Most of these faults were later filled with igneous rock as dikes which fed the laccoliths in the Mancos Shale. The second period of faulting accompanied the formation of those laccoliths intruded along the Navajo-Kayenta contact and produced the Mount Mellenthin fault, the most conspicuous fault in the Middle Mountain area. This fault appears to be the result of uplift by the Mount Peale bysmalith and the associated laccoliths. The third period of deformation was of much less intensity and appears to have produced minor faults in both the igneous and sedimentary rocks.

The Mount Mellenthin fault extends from the stock of Middle Mountain eastward through the ridge connecting Mount Mellenthin and Mount Peale, and into Dark Canyon. In Dark Canyon the fault curves northward, along the east border of Mount Mellenthin, and separates it from the Blue Lake laccolith. This arcuate fault is believed to mark the southern and eastern limits of the Mount Mellenthin laccolith prior to erosion. The outlier of igneous rock, which forms the knoll on the ridge between Mount Mellenthin and Mount Peale, just north of the fault, supports this hypothesis. Displacement along the fault differs from place to place, but it is probably as much as 500 feet on the ridge just described. The beds south and east of the fault are upthrown and are probably underlain, in part, by igneous rock that extends from the Mount Peale bysmalith northward into the Blue Lake area. It is probable that the underlying intrusives formed later than the Mount Mellenthin laccolith and that its mass prohibited the northward and westward movement of the magma of the younger intrusives. The constriction thus formed appears to have forced the magma upward and ruptured the overlying beds along the margin of the Mount Mellenthin laccolith.

A swarm of minor faults cross the ridge just south of Mount Mellenthin and may represent a third and final period of deformation in the Middle Mountain area. Both the igneous and underlying sedimentary rocks have been ruptured by two sets of semiparallel faults. One set bears due north, the other due west. Both sets lie in the center of the domal uplift which elevated the sedimentary and igneous rocks of Mount Peale and Mount Mellenthin during the final stage of igneous intrusion.

## STRUCTURAL HISTORY

The history of the structural features within the La Sal quadrangle is an integral but very small part of the history of the Colorado Plateau about which much has already been written. Beginning with the work of such pioneers as Powell (1875, 1876), Gilbert (1877), and Dutton (1880, 1882, 1885), much effort and time have been expended by many geologists in studying and piecing together the geologic history of this vast area. Much of the work is incorporated and published in reports of the U.S. Geological Survey. Publications that are more directly associated with the mapped area described in this report are the works of Baker (1933, 1946), Dane (1935), Gould (1926), Hunt (1953, 1954, 1956, and 1958), Cater (1954a), Shoemaker (1954, 1955, 1956a), and Withington (1956).

For a more complete structural history of the Colorado Plateau, the reader is referred to an article by Shoemaker (1954). Shoemaker describes the major uplifts and basins and attributes their formation to large-scale regional warping and strain of the basement complex; the salt cells and anticlines he attributes to flowage of plastic masses of evaporites, and the mountain domes, laccoliths, dikes, and diatremes to stress transmitted by magmatic pressure within the earth's crust. None of the mechanisms involved or their resultant structures is entirely separate; on the contrary, within the mapped area they are intimately intermeshed and give a revealing story of the structural history of this small part of the earth's crust.

All three types of stress mentioned by Shoemaker have affected the rocks within the La Sal quadrangle. Field evidence indicates that several periods of major deformation were interspersed with many minor periods. The first major period of deformation began either late in the Mississippian Period or Early Pennsylvanian time with downwarping and formation of a large structural basin, the Paradox Basin. The northeast side of the structural basin became outlined by the gradual emergence of the ancestral Uncompahgre highland. The basin began to fill with thick deposits of evaporite, limestone, and interbedded arkose (Cater, 1954a) of the Hermosa and Rico Formations. A second uplift along the Uncompahgre during the Permian Period resulted in deposition of the thick arkosic fanglomerates of the Cutler Formation. This uplift was accompanied by deformation in the basement complex which, in turn, caused flowage of salt in the Hermosa Formation. Initial growth of the salt cells is marked by pinchouts and thinning of the Cutler Formation on the flanks of Fisher Valley and Paradox Valley. This growth is also marked by the local absence of the Moenkopi on Moore's Ridge flanking South Mountain and a thinned sequence of Cutler beds on the flanks of both North and South Mountains and the west side of Sinbad Valley.

Through Late Triassic, Jurassic, and Early Cretaceous time, the area was structurally more stable. Thinning of the sedimentary rocks between the Cutler and Morrison Formations in the Gypsum Valley area (Stokes and Phoenix, 1948) reflects a gradual uplift of the salt anticlines. In the La Sal quadrangle this uplift is indicated by local thinning or absence of the Cutler, Moenkopi, Navajo, and Carmel(?) Formations along the flanks of the mountains and salt anticlines. Stokes (in Stokes and Phoenix, 1948) suggests that the close balance between the rise of salt and sedimentation indicates that growth of the salt masses was governed largely by the loading of sediments on their peripheries. The salt may have reached the surface in different places at different times. A quiescent period began with the deposition of the Morrison Formation and lasted until near the end of Dakota deposition. Stokes (in Stokes and Phoenix, 1948) also suggests that minor uplift of the salt masses may have occurred during deposition of the Burro Canyon Formation and Dakota

Sandstone, as indicated by thinning of the two formations. The present writers have found no evidence in the La Sal quadrangle to support this theory; they believe that thickness difference of the two formations is purely a function of erosional disconformity which separates them (Carter, 1957).

Epeirogenic downwarping of the Colorado Plateau during Dakota time allowed encroachment of marine waters which later deposited the Mancos Shale. Thicknesses of the Mancos Shale and the Mesaverde Group which crop out to the north (Fischer, 1936) indicate that about 5,500 feet of Upper Cretaceous sedimentary rocks once covered the mapped area. However, Upper Cretaceous beds younger than Laramie age are absent in the central part of the Plateau and those younger than Niobrara age are absent in the La Sal quadrangle. It is thus difficult to determine the precise time that igneous activity started in the La Sal Mountains, but if it is assumed that the laccolithic mountain groups of the Plateau, being of similar composition, are contemporaneous, a Late Cretaceous age is not inconceivable. Shoemaker (1954, p. 63) states that the McDermott Member of the Animas Formation, which underlies the Ojo Alamo Sandstone of latest Cretaceous age (Laramie or Hell Creek) (Reeside, 1924; Cobban and Reeside, 1952), near Durango, Colo., contains large boulders of diorite porphyry that are lithologically similar to and appear to be derived from the igneous centers of the La Plata Mountains. He concludes that some of the intrusions in the La Plata Mountains are probably of Late Cretaceous age. No evidence was found in the mapped area to preclude such an age for commencement of intrusion that produced the La Sal Mountains.

Intrusion of the salt anticlines by the North and South Mountains laccoliths came early in the formation of the La Sal Mountains and was apparently started by renewed faulting of the crust along northwest-striking zones of weakness. Magma gradually filled and eventually ruptured the crests of the anticlines as plastic exaporite beds were pushed outward along the strike of the folds. As cooling and crystallization of the magma in North and South Mountains took place, the original escape routes probably became clogged and intrusion was forced along secondary zones of weakness. The remarkable north-south alinement of the three mountain stocks suggests that secondary faults in the crust may parallel this direction. The emplacement of Middle Mountain apparently was somewhat later and was restricted by proximity of the other two masses. Earliest intrusion in the Middle Mountain area was at the central stock and radial dikes and formed the Mellenthin laccolith. The Mount Peale bysmalith, Twomile Creek laccolith, and Blue Lake laccolith were intruded at horizons much lower in the stratigraphic column, and fault displacements suggest that they were later than the Mellenthin laccolith.

The last stage of intrusion in the La Sal Mountains is marked by the presence of breccia pipes in the North Mountain intrusive. Hunt (1954) suggests that rupture and possibly erosion near the crest of the mountain may have allowed the syenitic intrusion to break through the surface explosively.

Zircon age determinations of syenite and monzonite porphyry by H. W. Jaffe indicate that the youngest igneous rocks are of middle Eocene age. The diorite porphyry is intruded by the monzonite porphyry and intrudes rocks no younger than the Mancos Shale of Late Cretaceous age; all younger sedimentary rocks have been removed by erosion in the mountain area. This relation limits the emplacement of the great bulk of the igneous rocks of the La Sal Mountains to some time between the Late Cretaceous and middle Eocene and indicates that intrusive processes spanned a period of at least 20 million years.

After the igneous uplift of the La Sal Mountains came a period of erosion and structural collapse of the salt anticlines. Fans of sand and gravel were deposited on the flanks of the mountain uplift during Pliocene(?) time. Large fanglomerate deposits crop out in the Taylor Creek syncline in the mapped area, in Castle Valley to the north, and in Pack Creek to the west. Post-fanglomerate tilting probably resulted from erosion, solution, and settling adjustments of plastic evaporite beds in Castle Valley and in the Taylor Creek syncline.

Recent deformation is believed to be restricted to block faulting along the valley margins; local adjustments in the plastic evaporite cores of the breached anticlines is indicated by small faults and minor folds in the Quaternary deposits.

## URANIUM DEPOSITS

### HISTORY OF MINING IN THE LA SAL QUADRANGLE

The early history of discovery and development of uranium-vanadium ores of the Colorado Plateau centers in areas around Paradox Valley that are both adjacent to and within the mapped area. Publications by Burwell (1920) and Coffin (1921 and 1954) describe most of the history of these discoveries and the growth of the uranium-vanadium industry. The following paragraphs summarize the principal historical events in the development of the La Sal Creek mining district and provide the background which led to the studies contained in this report.

Prior to 1880, white settlers knew that local Indians obtained a yellow pigment from the Yellow Bird and other nearby deposits. These deposits were sampled by Gordon Kimball, a mining engineer at the Cashin mine. The samples and others from deposits in Roc Creek were shipped to France for study by Mr. Charles Poulot (Kimball, 1904), who identified the material as uranium ore. Thereafter small tonnages were mined periodically for research.

It was not until 1913, however, when war threatened that intensive mining for vanadium began at the La Sal Creek Yellow Bird deposits. Mining continued until 1921 when demand declined, owing to flooding of the market by cheaper Belgian Congo ores. Activity was renewed in 1936 as, again, war threatened. Vanadium was of principal interest during the late thirties, but as atomic research and technology progressed, the emphasis gradually changed to interest in uranium. In 1942, special exploration studies and purchasing programs were started under the Metals Reserve Co., and later the Manhattan Project, to stimulate development of uranium-vanadium deposits. Under the Manhattan project, C. W. Livingston (1945, unpub. data) made a detailed study of the mines of the La Sal Creek district. Exploration and development were left to the mine operators. U.S. Vanadium Corp. drilled about 100 holes with wagon and diamond drills at their properties in the northeast part of the district.

The end of World War II brought another decline in the demand for uranium and vanadium and most of the mines in the La Sal Creek area closed. In the early fifties the Korean conflict and threat of world domination by Communism brought renewed search for uranium resources to be used in atomic weapons and as energy for peaceful purposes.

In 1952 the U.S. Geological Survey began a program of development drilling in the vicinity of the Evening Star and Gray Daun mines to outline new ore bodies and extensions of known deposits. This drilling resulted in the discovery of the Marjorie Ann and Firefly-Pigmay deposits. Mining operations began on these properties in 1953. Close-spaced development drilling behind the Vanadium Queen mine found new ore bodies and discovered favorable ground extending in a northeasterly direction from the mine workings. A wide-spaced drilling pattern (holes spaced 500 to 1,000 ft apart) was then employed and resulted in the discovery of a favorable belt of ground about 1,000 to 3,000 feet wide and about 3 miles long extending from the Vanadium Queen mine to the mines along Lion Canyon. Exploratory drilling on a wide-spaced pattern was continued through 1954 both north and south of La Sal Creek canyon to further define the favorable area and to search for other areas which might be favorable for the localization of uranium deposits. The location of the drill holes is shown in plate 4. Private interest in exploration and development in the area increased during 1954 and the government exploratory drilling program was terminated.

The discovery of extensions of known deposits renewed production in the Gray Daun, Vanadium Queen, Hesperus, and Evening Star mines. Of the new deposits discovered and partly outlined by drilling, only the Marjorie Ann, Firefly-Pigmay, and Black Hat claims had been developed and were being mined by the end of 1956. Known production in the area had increased from 18,260 short tons during the period 1940–44 (Livingston, written commun., 1945), to a total of 42,410 short tons by the end of 1954.

The discovery in 1955 of a deposit on Hop Creek, about 1½ miles north of the Gray Daun mine, and another near the east flank of Mount Mellenthin, indicates that other favorable belts and similar deposits may be present within the mapped area. In 1957, when this study terminated, mining in the La Sal Creek district continued at a high rate.

### DISTRIBUTION

Uranium-vanadium deposits occur in the Brushy Basin and Salt Wash Members of the Morrison Formation in the La Sal quadrangle. The vertical distribution is narrow, for almost all of the deposits lie within a sequence of sedimentary rock that is about 150 feet thick. This sequence includes strata both above and below the contact of the two members. The majority and largest of these deposits are in the uppermost continuous sandstone of the Salt Wash Member; this unit is referred to as the "ore-bearing sandstone." A few small deposits have been discovered in a discontinuous sandstone lens of the Salt Wash that overlies the ore-bearing sandstone. Most deposits in the Brushy Basin Member are restricted to conglomeratic sandstone lenses at the base of the member. A few deposits, however, occur in sandstone lenses in the upper part of the Brushy Basin Member.

The areal distribution of the deposits, when considered as a whole, appears wide and erratic (pl. 5). It is best, however, to consider the geographic distribution of these deposits according to their stratigraphic position.

The deposits in the Brushy Basin Member, discovered chiefly by surface prospecting, are erratically distributed over a wide area. Most of the deposits are in a cherty conglomeratic sandstone, commonly referred to as the "Christmas tree conglomerate," which in places is the base of the Brushy Basin Member. Mineralized material is also associated with carbonaceous material, green mudstone, and siltstone strata at various levels throughout the member. The Sumner mine, near the headwaters of Ice Lake Creek (pl. 3), is typical of Brushy Basin deposits in that it is small and occurs in the basal unit of the member. Similar deposits were found by Survey drilling but few were thoroughly explored because they were generally too small and, in most places, too deep to be mined profitably. An unusually high concentration of deposits in the Brushy Basin Member is found in the vicinity of Wray Mesa, south of La Sal Creek. These deposits are in the lower 200 feet of the Brushy Basin Member and were mined in 1953–55 both by underground and open-pit methods. They include the Lucky No. 1, Morning Glory, Howling Coyote, Too High, and Brushy Basin No. 1 and 3 mines. The Morning Glory and Howling Coyote deposits are at the east end of Wray Mesa, east of the La Sal quadrangle, and are therefore not shown on the maps.

A few deposits are in a discontinuous sandstone bed that is less than 25 feet thick and lies about 10 feet above the ore-bearing sandstone layer of the Salt Wash Member. The Hesperus, Uranium Girl (formerly Emergency), and the upper workings of the Maud mine, along the north and south rims of La Sal Creek canyon, are examples of deposits in this sandstone. The deposits are small, and have thus far produced a combined total of a few hundred tons of ore. The ore minerals are generally oxidized, and are mostly carnotite and tyuyamunite associated with and replacing carbonaceous material. These deposits are widely spaced and erratic.

Most of the uranium deposits in the La Sal Creek area are in the uppermost continuous sandstone unit of the Salt Wash Member which is commonly referred to as the "third rim" or the ore-bearing sandstone. This unit is in the stratigraphic interval between 250 and 350 feet above the Entrada Sandstone or 350 to 450 feet below the base of the Burro Canyon Formation. The deposits in the La Sal Creek area are concentrated in a northeast-trending belt of favorable ground which is 1,000 to 3,000 feet wide and at least 5 miles long. This belt is referred to as the "La Sal Creek mineral belt" (pl. 5). The western extremity of this belt has not been clearly defined.

Within the belt, individual deposits are elongate and their long axes commonly trend east or southeast at a slight angle to the overall trend of the favorable area, somewhat as do the deposits within favorable parts of the Uravan mineral belt as defined by Fischer and Hilpert (1952). The deposits are generally in the lowermost 20 feet of the sandstone and are separated by barren or weakly mineralized lenses of sandstone or mudstone. The horizontal distance between deposits ranges from 100 to 600 feet.

The regional relation between the La Sal Creek deposits and the Uravan mineral belt described by Fischer and Hilpert (1952) is somewhat obscure. Trends of sedimentary structures indicate that prior to uplift, erosion, and collapse of the Paradox anticline, the La Sal Creek belt probably continued eastward where it joined the favorable ground on Carpenter Ridge and may have reached as far south as Club Mesa near Uravan, Colo. These areas lie on the northeast flank of the Paradox anticline east of the map boundary.

The authors believe that there are other favorable areas in the vicinity of the La Sal Creek mining district and the La Sal Mountains. This belief is based on field observations of the Salt Wash Member and of small, scattered uranium-vanadium deposits outside the explored favorable area. These deposits may lie in zones that have trends, dimensions, and ore bodies similar to those in the La Sal Creek district. The extent, distribution, and nature of such potential areas is not known, but their locations and possibilities are discussed on page 73.

### SIZE AND SHAPE

The deposits in the Morrison Formation are of various sizes and shapes. In general, they are layered concentrates of uranium-vanadium minerals occurring as isolated ore bodies or as interconnected clusters of ore bodies. The bodies are greatly varied in thickness and areal extent; they may be flat-lying to gently undulating tabular deposits or may occur as rolls. In places the ore deposits occur where ore minerals replace carbonaceous material in "trash pockets" and fossil logs. All these types of ore bodies occur in both members of the formation, but the largest and most varied in shape are the deposits in the Salt Wash Member.

The flat-lying tabular deposits may occur as single layers as much as 3 feet thick, or as several thinner superposed layers separated by barren sandstone. Locally several layers join and form a composite layer as much as 12 feet thick. These layers generally are thicker in some places and thinner in others in conformation with bedding planes inherent in the sandstone lenses or with surfaces of mudstone layers separating sandstone lenses. Drill-hole data and mine mapping indicate that the average ore thickness in the area is about 3 feet.

The layered deposits are extremely varied in size. They range from isolated ore bodies covering a few tens of square feet and containing a few tons of ore to clusters of ore bodies that are generally interconnected by thin layers of weakly mineralized sandstone or mudstone; these ore bodies cover areas as much as 600 feet long and 300 feet wide and contain as much as 20,000 tons of ore. Where these bodies occur in closely spaced clusters, from 10,000 to 50,000 tons of ore can be produced from a single mine. The orientation and indicated or inferred limits of these deposits are shown on the mine maps (pls. 6–13). In general, they parallel the average direction of roll axes and trends of sedimentary structures. Most deposits in the La Sal Creek mineral belt trend between N. 70° E. and S. 70° E. A few, however, are widely divergent from this trend and probably reflect locally divergent directions of Salt Wash stream flow.

The range in trend of sedimentary structures suggests that the ore-bearing sandstone was deposited by meandering streams. Widely divergent bearings may be due, in part, to the difficulty in obtaining enough accurate measurements from the ore-bearing sandstone. According to Raup and Miesch (1957), the number of cross-stratification (unidirectional) measurements obtained are approximately half those required for firmly based conclusions. This paucity of measurements is explained by the fact that in mining most of the ore-bearing sandstone lens is removed with the ore and only the barren lenses which are usually coated by dust and mud from blasting are left.

Rolls are layered ore bodies of a great variety of forms that curve sharply across the sandstone bedding. They most commonly display rough C and S shapes in cross section, usually with some irregularity in the limbs. Many rolls are C-shaped but the C is turned on its side and the outside roll surface is either convex upward or downward. Less abundant are the more complex "socket" and "mirror-image" rolls described by Shawe (1956). In plan, the rolls are elongate or linear bodies which may be straight but more commonly are curved to some degree.

The roll surfaces that separate mineralized material from barren rock have been described as "fractures" (D. R. Shawe, oral commun., 1955, Y. W. Isachsen, oral commun., 1955). The term "fracture" usually refers to a break or separation and is generally associated with other results of deformation. Rather than imply a deformational process in the formation of roll ore bodies, the authors prefer to consider the roll surface as a mineral contact along which a zone of weakness or a parting surface may form during mining as a result of differences in either degree of cementation or in gross composition of the ore body and the surrounding wallrock. Differences on either side of the contact allow the roll to break away from a smooth surface of barren rock when mined. Many of these surfaces are minutely undulatory, and a thin scale or crust of mineralized material remains on the surface after mining. Such a surface is referred to as a "roll scab."

Log replacement and trash-pocket ore bodies are considerably smaller but of higher grade than other ore bodies. Logs contain very high grade material and are as much as 30 feet long and 1 to 2 feet in diameter. Many of the larger ones are oriented parallel to the dips of adjacent cross-stratified beds. The trash pockets are podlike accumulations of poorly sorted sandstone, fragments of carbonaceous matter, and mudstone or clay galls that are partly impregnated with, and in part replaced by, uranium and vanadium minerals. These pockets are rarely more than a few feet long, are a foot or two thick, and are of various shapes. Some pockets are circular in plan and appear to represent accumulations deposited by small whirlpools or eddies in Salt Wash streams; others are elongate and fill minor channel scours. The direction of elongation of such bodies generally agrees with directions determined by cross-stratification measurements in subjacent sandstone beds.

In the Brushy Basin Member, mineralized material occurs in all four types of ore bodies just described. The layered deposits are from 0 to more than 1 foot thick and cover areas as much as a few hundred square feet. These bodies contain from several pounds to a few hundred tons of mineralized material. The podlike ore bodies are small and contain volumes of rock from a few cubic inches to a few cubic feet. Roll ore bodies are uncommon and generally small. An exception to this, however, is the ore body at the Lucky No. 1 mine at the head of Sharp Canyon on the east end of Wray Mesa. The ore body is a C-shaped roll that is approximately 90 feet long, about 3 feet high, and from 1 to 3 feet wide. The trend of the roll axis forms a gentle arc that bears from N. 25° E. on the west end to N. 50° E. on the east. Ore was concentrated along the convex side of the surface along which the trend measurements were made.

### LOCALIZATION

The structural features that probably control the localization of uranium-vanadium deposits of the Colorado Plateau may be divided into two distinct types: those of sedimentary origin and those of tectonic origin. Most deposits of the La Sal Creek area are in the lower part of the uppermost continuous sandstone stratum of the Salt Wash. In this host rock, sedimentary features present the most obvious control of position and, usually, of the shape of the ore bodies.

An isopach map (fig. 6) showing the thickness of sedimentary rocks between the base of the ore-bearing sandstone and the top of the Entrada Sandstone gives a general picture of the surface on which the ore-bearing unit was deposited. The most conspicuous feature is a roughly circular basin in the central part of the area

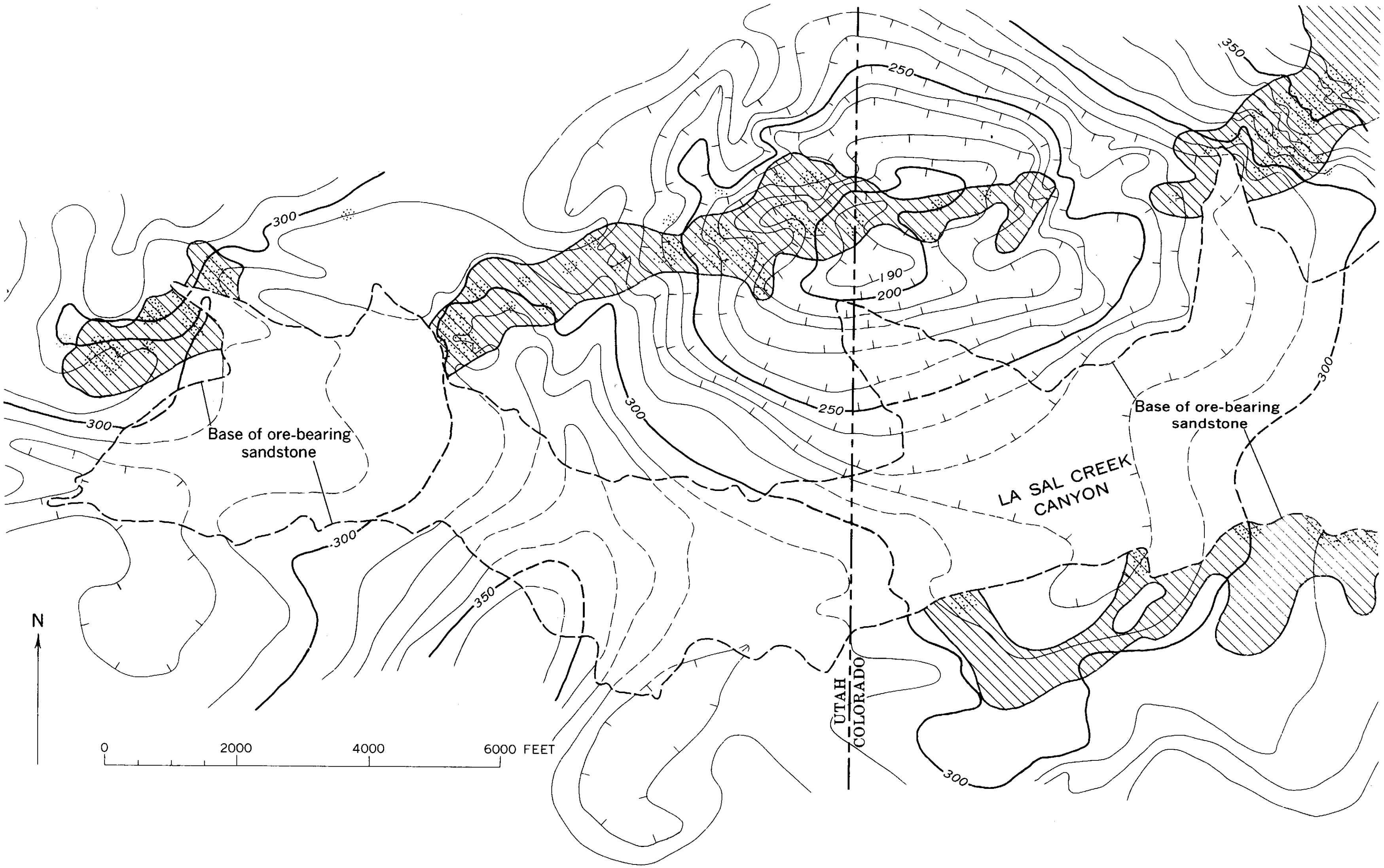



Figure 6.—Isopach map of part of the La Sal Creek area showing thickness of strata from the top of the Entrada Sandstone to the base of the ore-bearing sandstone of the Salt Wash Member. Contours, short dashed where projected, reflect the configuration of the surface upon which the ore-bearing sandstone was deposited. Contour interval is 10 feet. In 1954, the overlying sandstone contained known uranium-vanadium deposits in the stippled area, and potential deposits in the ruled area.

near the Utah-Colorado line. It is in this area, generally outlined by the 280-foot isopach, that the thickest sandstone of the ore-bearing unit in the Morrison Formation was penetrated during the drilling program. The outcrop of the one-bearing sandstone along the north side of the La Sal Creek canyon is also thickest and most prominent in this area. Ore deposits of this area are generally in the middle or upper half of the sandstone stratum, whereas deposits that occur outside the 280-foot isopach are near or at the base of the sandstone.

Areas outside the 280-foot isopach represent local thickening in the underlying sedimentary strata. These areas were probably highs during deposition of the ore-bearing unit and locally controlled the course of the depositing stream. The greater thickness shown in the northeast corner of the figure may also have been a topographic high or it may represent a thickening near the margin of the Paradox anticline resulting from local subsidence caused by salt movement from this area eastward into areas of uplift. Recent erosion of the ore-bearing sandstone and underlying strata east of the mapped area make the picture incomplete.

The general configuration of the surface suggests that, while the major flow of the Salt Wash stream was northeastward through the center of the basin, a local channel passed through the southeastern part of the basin. Sedimentary structures, logs, and roll directions (see "Yellow Bird mine," p. 71) in this area indicate that the southeastern channel turned north and probably joined the principal channel in the northeast corner of the mapped area (fig. 6). The irregular surface seen at the west edge of the area (fig. 6) suggests that favorable ground and possibly more deposits may be west of the explored area.

The ore-bearing sandstone layer overlies impermeable mudstone and siltstone beds. Structure contours drawn at 10-foot intervals at the base of the ore-bearing sandstone and based on elevations compiled from diamond-drill-hole data show that the surface of deposition was irregular. Most of the mineral deposits lie in broad shallow depressions or scours near and on the flanks and crests of structural noses (fig. 7). These noses appear to project into the main channel where the uppermost sandstone beds of the Salt Wash were deposited. This channel is contained in the belt of favorable ground in the La Sal Creek area. Within this belt, the maximum relief from the lowest depression to the top of the highest nose is about 50 feet.

The deposits also lie in shallow depressions, best seen in the Gray Daun mine (pl. 8) and the Vanadium Queen mine (pl. 12); these depressions appear to be similar to local scours in the channel floors of present-day meandering braided streams. The structural noses can be likened to cuspate projections along the margins of streambeds. Such depressions and projections create eddies and whirlpools in which a great amount of woody debris collects, becomes waterlogged, and sinks. During floods, however, debris is rafted onto the higher bars and cusps within and along the margins of the channel. Such a process may explain the placement of many of the trash-pocket accumulations of carbonaceous debris associated with the uranium-vanadium ores in the Salt Wash Member.

The ore-bearing sandstone beds fill these depressions and are commonly capped by impervious layers of green mudstone as shown in section $A-A'$ of the Vanadium Queen (pl. 12) and in section $A-A'$ of the Firefly-Pigmay mines (pl. 7). The sandstone in the channels is highly lenticular and complexly crossbedded. "Festoon cross lamination" (Knight, 1930) is common and may have controlled localization of the more tabular ore bodies in a manner similar to that described by Roach and Thompson (1959). The festoons are composed of finely laminated sandstone that fills secondary stream scours or troughs within a channel. These sand-filled troughs intersect with, overlap, or are superimposed on other festoons. The surfaces separating the festoons are commonly thin clay films or seams that are much less permeable than the sandstone within the festoons. These features along with the mudstone beds, which range from thin films to several feet in thickness, separate large sandstone lenses composed of many festoons and appear to be the reason, in part, for the highly variable transmissivity of Salt Wash sandstones as reported by Jobin (1956). Thus, sedimentary features such as channel scours, sandstone lenses, mudstone seams, and festoon cross laminations combine as important factors in localizing uranium-vanadium-bearing solutions.

The localization and configuration of roll ore bodies have been attributed to both obvious and obscure features. The close association of roll and tabular-type ore bodies suggests an interplay of sedimentary features and the agent that transported the ore minerals to their present site. A variety of transporting agents have been postulated for the ore-carrying fluid and are considered in detail on page 52.

The roll surfaces appear to represent the contact between two immiscible substances which were in either a liquid or gaseous state at the time of localization. The long axes of the rolls tend to parallel the trends of sedimentary structures, that is, the direction of paleostream flow, and reflect the orientation of the most permeable units in the sandstone layers (Lowell, 1955; Shawe, 1956). Demonstration of this relationship

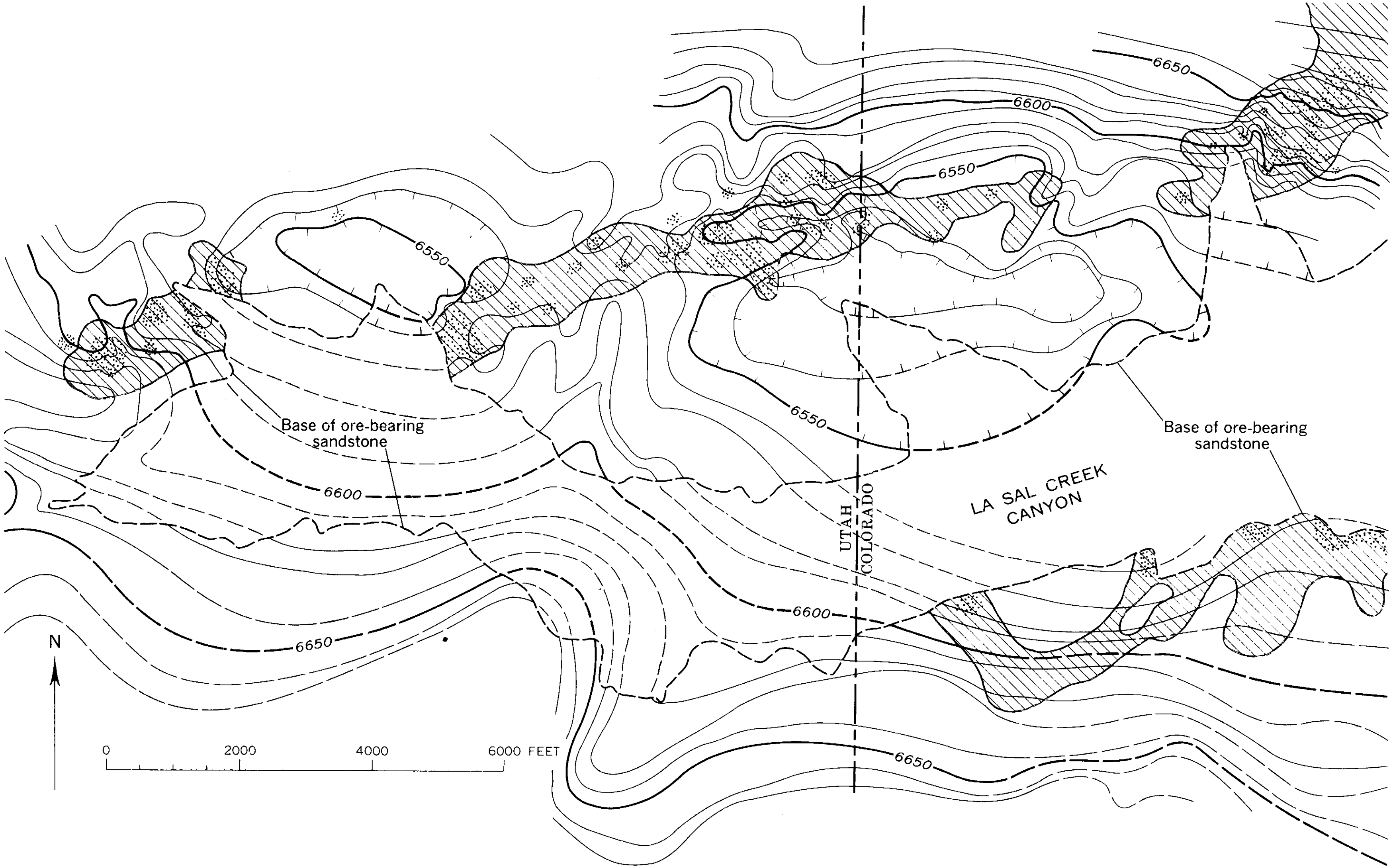



**Figure 7.**—Structure contour map of the base of the ore-bearing sandstone of the Salt Wash Member in part of the La Sal Creek area. Contours, dashed where located approximately and short dashed where projected, reflect the configuration of the surface upon which the ore-bearing sandstone was deposited. Contour interval 10 feet; datum is near sea level. In 1954 the overlying sandstones contained known uranium-vanadium deposits in the stippled areas and potential deposits in the ruled areas.

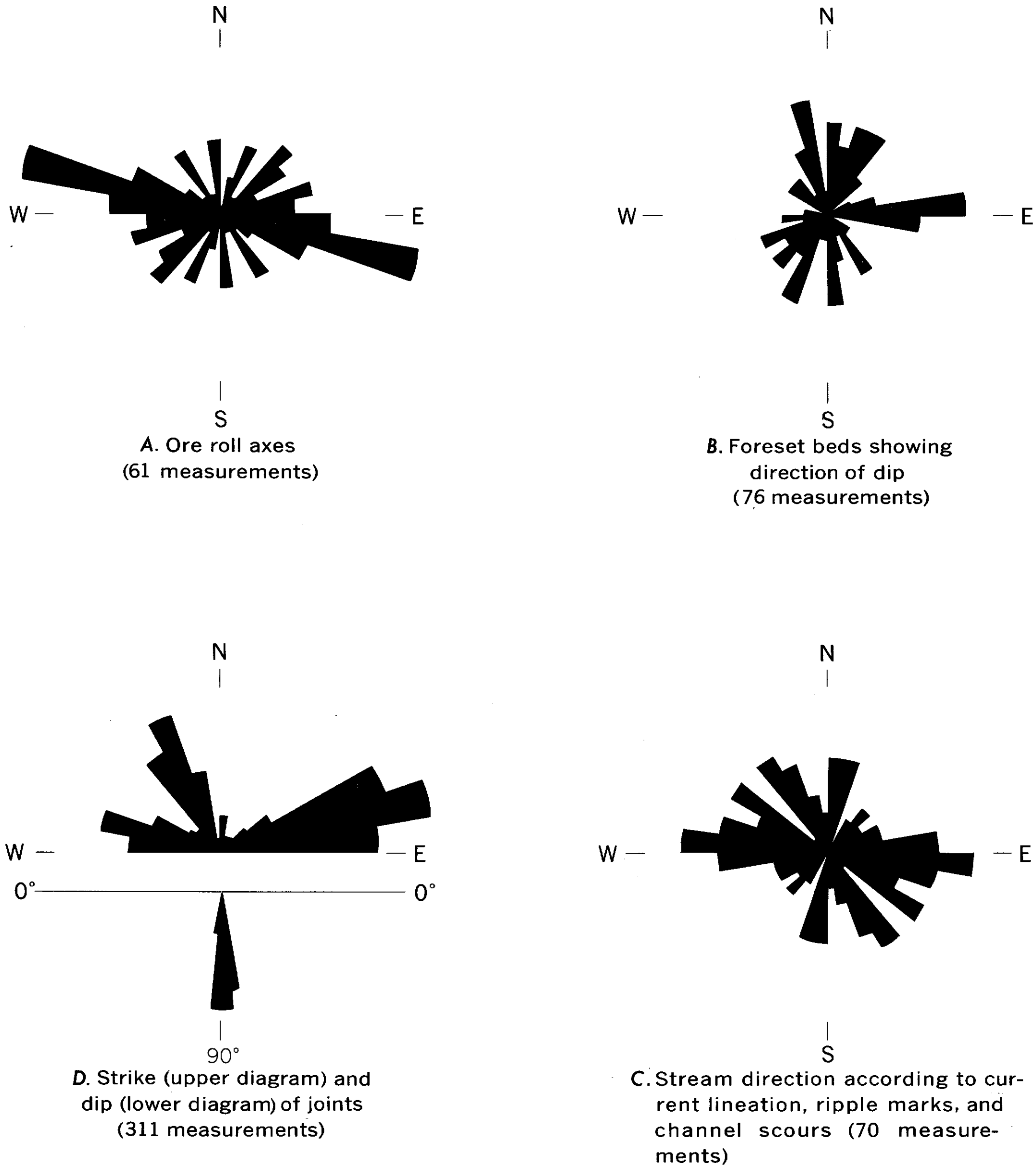



FIGURE 8.—Composite orientation diagrams showing trends of (*A*) ore roll axes, (*B*) unidirectional and (*C*) bidirectional sedimentary structures indicating direction of stream flow, (*D*) strike and dip of joint surfaces measured in all mines mapped in the La Sal Creek area.

by use of directional diagrams constructed for each of the mines that have been mapped in the La Sal Creek area and by a composite of these diagrams (fig. 8) is impaired by a lack of sufficient readings. The ore bodies and the host sandstone beds appear to be very much like the shoestring-sand type of stratigraphic trap searched for by the petroleum industry. Other similarities to stratigraphic traps will be considered on page 49.

There is no obvious relation of the localization of the ore deposits to tectonic structures. La Sal Creek mineral belt crosses the axis of the La Sal Creek sycline at an angle of about 20°. The mineral belt also extends between and lies on the flanks of two collapsed folds. One is part of the Paradox anticline and the other is the Pine Ridge anticline. The belt may extend eastward to the Valley View mine on Carpenter Ridge and westward to the Rattlesnake mine west of La Sal. No evidence has yet been found to indicate that these structures affected the localization of deposits. The distribution of known deposits outside the belt but within the mapped area suggests that other mineral belts may be present in different structural environments. To the south, the Uravan mineral belt appears to have crossed all major structural features prior to deformation and collapse.

Only two major faults were found in the La Sal Creek area, the Dugway fault (pl. 3) which delineates a part of the southwest flank of the collapsed Paradox anticline, and the Sharp Canyon fault which is approximately perpendicular to the Dugway fault and is in Sharp Canyon southeast of the mineral belt. Both faults contain copper oxides and sulfides, for which they have been prospected, but neither is known to contain uranium-vanadium minerals, nor do they appear to be related to the introduction or localization of uranium-vanadium-bearing solutions in the La Sal Creek area.

Only two deposits within the La Sal quadrangle are known to be associated with faults; the Valley View deposit (sec. 7, T. 48 N., R. 19 W.) adjacent to the Valley View fault, and the Jackpot deposit (sec. 2, T. 48 N., R. 20 W.) close to a fault subsidiary to the Valley View fault. The Valley View deposit is in strata of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. Part of the deposit lies in beds that have been fractured and dragged upward at a steep angle, but otherwise the deposit displays characteristics common to other Salt Wash ore bodies. The association of the deposit to the fault is thought to be happenstance; the deposit existed prior to faulting and was intersected by the fault. The deposit is more fully discussed on page 67.

The Jackpot deposit is in highly fractured Wingate Sandstone adjacent to a fault. The deposit consists principally of oxidized uranium-vanadium minerals coating fracture surfaces. The components of the ore were probably carried there by ground water from one or more nearby deposits. The Jackpot is the only known deposit in the La Sal quadrangle that is fault controlled. This deposit is discussed more fully on page 62.

Joints are common, as can be seen on the accompanying mine maps. Two dominant joint sets are apparent and are related to the folds and faults in the area. Joint diagrams for individual mines show that there is little relationship between the joints and trends of ore bodies. Secondary minerals such as carnotite, tyuyamunite, hewettite, and pascoite are found on joint surfaces in both the oxidized and unoxidized deposits, and appear to have been transported by Recent groundwater movements.

## MINERALOGY

The uranium-vanadium deposits of the La Sal Creek area are composed of fine-grained mineral aggregates which fill pore spaces in sandstone, and coat and locally, partly replace sandstone. These aggregates are considered ore grade when they occur in rock 1 foot or more thick that contains 0.10 percent or more $U_3O_8$ and (or) 1.00 percent or more $V_2O_5$. Rock containing less than this amount but containing 0.02 percent or more $U_3O_8$ and (or) 0.10 percent or more $V_2O_5$, regardless of thickness, is considered mineralized. In this study, rock from drill cores and hand samples containing as little as 0.02 percent $U_3O_8$ or 0.20 percent $V_2O_5$ was recognized and chemically analyzed. In some places the presence of these trace amounts led to discovery of minable ore bodies.

The deposits of the La Sal Creek area are rich in vanadium oxide which on the average is approximately six times more abundant than uranium oxide. Vanadium: uranium ratios differ considerably from deposit to deposit and range from 4:1 to 14:1 parts $V_2O_5$ to $U_3O_8$. Studies of ore samples collected from several of the mines have recently been completed by A. D. Weeks, M. E. Thompson, and others of the U.S. Geological Survey. Weeks (written commun., 1957) indicates that this predominance of vanadium over uranium in the La Sal Creek area is reflected in the mineralogy, and that the vanadium silicates are more abundant than other vanadium, uranium, or uranium-vanadium minerals.

Minerals that have been either tentatively or positively identified in the deposits of the La Sal Creek area and vicinity and the mines in which they were found are listed in table 1. Details of these occurrences are given in the discussion of individual mines. The assemblages shown for the various mines are probably not complete because positive identification of many uranium or vanadium minerals by megascopic methods is nearly impossible, owing to the close similarities in crystal form, color, and mode of occurrence. The time alloted to underground mine studies allowed only selective sampling of the various ore bodies by visual inspection.

As a whole, the suite of minerals comprising the ore is large, but in certain mines the assemblage is small. Two factors may be responsible for this difference between individual deposits: differences in the original chemistry of the deposits, or differences in the degree of oxidation to which the ore minerals of the deposits have been subjected.

Details of the original chemistry of the deposits and their wallrocks are not thoroughly known, although much study has been devoted to the mineralogy and trace-element composition and distribution of Colorado Plateau ore deposits. The composition of the mineral assemblages of certain deposits apparently reflect the proportions of metallic constituents present in the orig-

TABLE 1.—*Minerals identified in ores of the La Sal quadrangle, and their vanadium-uranium ratios*

[?, tentative identification]

| Mineral | Mine and its $V_2O_5$:$U_3O_8$ ratio (in parentheses) | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Angle (4:1) | Black Hat (7:1) | Brushy Basin 1 (6:1) | Brushy Basin 3 (6:1) | Confusion (4:1) | Elray (6:1) | Evening Star (8:1) | Firefly-Pigmay (6:1) | Gray Daun (5:1) | Hesperus (4:1) | Jackpot (9:1) | Little Don (12:1) | Little Peter (4:1) | Lucky 1 (8:1) | Marjorie Ann (5:1) | Maud (7:1) | Morning Star (14:1) | New Yellow Spot (11:1) | Sumner (12:1) | Too High (7:1) | Uranium Girl (8:1) | Valley View (4:1) | Vanadium Queen (8:1) | Vista Grande (6:1) | Wedge (4:1) | Yip Yip 1 (4:1) | Yellow Bird group (5:1) |
| *Uranium minerals* | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Boltwoodite | - | - | - | - | - | - | - | - | ? | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Carnotite | × | - | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| Coffinite | - | - | - | - | - | - | - | × | × | - | - | - | - | - | - | - | - | - | - | - | - | ? | × | - | - | - | |
| Gummite | - | - | - | - | - | - | - | - | - | - | - | - | ? | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Phosphuranylite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Rauvite | - | - | - | - | - | - | - | - | - | - | - | - | ? | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Schroeckingerite | - | - | - | ? | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Saléeite-novacekite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Torbernite (or meta-) | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Tyuyamunite (or meta-) | × | - | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| Uraninite | - | × | - | - | - | - | - | × | × | - | - | - | - | - | - | - | - | - | - | - | - | ? | × | - | - | - | |
| Uraninite (amorphous) | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Uranophane | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Beta-uranophane | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Uranospathite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Metazeunerite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| *Vanadium minerals* | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Corvusite | - | × | - | - | - | - | ? | × | × | - | - | - | ? | - | - | - | - | - | - | - | - | ? | × | - | - | - | |
| Doloresite | - | ? | - | - | - | - | ? | ? | ? | - | - | - | ? | - | - | - | - | - | - | - | - | ? | ? | - | - | - | |
| Fervanite | - | - | - | - | - | - | ? | - | ? | - | - | - | - | - | ? | - | - | - | - | - | - | - | ? | - | - | - | |
| Hewettite | - | - | - | - | - | - | × | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | × | - | - | - | |
| Metahewettite | - | - | - | - | - | - | ? | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | ? | - | - | - | |
| Hummerite | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | ? |
| Melanovanadite | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | × | - | - | - | |
| Montroseite | - | × | - | - | - | - | - | × | × | ? | - | - | - | - | - | - | - | - | - | - | - | × | × | - | - | - | × |
| Paramontroseite | - | ? | - | - | - | - | - | ? | ? | ? | - | - | - | - | - | - | - | - | - | - | - | ? | ? | - | - | - | ? |
| Nolanite | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | × | - | - | - | |
| Pascoite | - | - | - | - | - | - | - | ? | ? | ? | - | - | ? | - | - | - | - | - | - | - | - | ? | ? | - | - | - | ? |
| Roscoelite | × | × | ? | ? | × | ? | × | × | × | × | ? | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| Simplotite | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | × | - | - | - | |
| Vanadium hydromica | × | × | × | × | × | × | × | × | × | × | ? | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| *Accessory sulfide minerals* | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Chalcocite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Chalcopyrite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Clausthalite | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Covellite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Galena | - | - | - | - | - | - | - | × | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Pyrite | - | × | - | - | - | - | - | × | × | - | - | - | - | - | - | - | - | - | - | - | - | - | × | - | - | - | |
| Sphalerite | - | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Tennantite | - | - | - | - | - | - | - | × | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |

inal ore solution or possibly a composite of several solutions which have in one way or another affected the deposits.

Individual deposits can be classified as being either oxidized or unoxidized, although each may display various degrees of oxidation. The greatest mineral assemblage is in deposits that contain both unoxidized and oxidized ore minerals. (See Gray Daun mine, table 1.) Oxidation and leaching may be partly responsible for the ratio of vanadium to uranium, for those deposits having the highest ratio generally have the smallest mineral assemblage and are, in general, in the eastern part of the area where uplift of the Paradox anticline and headward erosion of La Sal Creek first exposed the ore-bearing sandstone and caused a subsequent fall of the water table. Here the beds dip toward La Sal Creek canyon, which affords an outlet for ground water. In contrast, most of the deposits that have low ratios of $V_2O_5$ to $U_3O_8$ are either deeply buried or lie near the head of La Sal Creek canyon where exposure of the ore-bearing sandstone has been limited.

Oxidized ore consists largely of vanadium hydromica and finely disseminated carnotite and limonite. Where carnotite and limonite are sufficiently concentrated to impart a speckled or spotted appearance to the rock, it is referred to as "rattlesnake ore." Oxidized ore was found in the New Yellow Spot, Marjorie Ann, Evening Star, Yellow Bird, and adjacent mines at the eastern end of the La Sal Creek mining district.

Examples of deposits little affected by oxidation are in the Black Hat, Firefly-Pigmay, and Vanadium Queen mines, where the ore is almost unoxidized, and in the Gray Daun mine which contains both unoxidized and oxidized ore minerals that represent the entire oxidation sequence. In the first three mines the ore-bearing sandstone lenses are saturated with ground water which appears to have been trapped by impervious layers of mudstone that enclose the lenses. The ore is bluish black, greenish black, an off shade of black, and, in places, brown. The brown material may be partly oxidized. The unoxidized ore minerals are roscoelite, vanadium hydromica, coffinite, and uraninite. Sparse amounts of metallic sulfides are associated with the uranium minerals. The most abundant of these is pyrite, in places closely associated with lesser amounts of chalcocite, chalcopyrite, galena, covellite, and tennantite. Minor amounts of the selenide, clausthalite, have also been identified.

In the Gray Daun mine around unoxidized ore bodies there is an ill-defined zone of partially oxidized vanadium and uranium minerals. The vanadium minerals include montroseite, doloresite(?), paramontroseite, corvusite, and traces of simplotite and melanovanadite. The uranium minerals include the uranyl phosphates torbernite, metatorbernite, and phosphuranylite, the uranyl arsenates metazeunerite and saléeite-novacekite, and the uranyl silicates uranophane, beta-uranophane, and a mineral resembling boltwoodite (A. D. Weeks, written commun., 1957). Mrs. Weeks describes a black substance, resembling coalified wood, that gives an X-ray pattern unlike uraninite and which she believes may represent "an amorphous phase in an oxidation stage between uraninite and the uranyl minerals." Minerals that represent a more advanced state of oxidation occur in the partly saturated parts of the deposits.

The most highly oxidized deposits, those between Lion Creek and Ice Lake canyons and of the Yellow Bird groups of mines, are in beds that are covered by little or no overburden and that dip gently toward La Sal Creek canyon. In these the dominant ore minerals are roscoelite, vanadium hydromica, carnotite, and tyuyamunite, and minor amounts of fervanite (?), hewettite, and metahewettite. Most of the metallic sulfides have been oxidized to hematite and limonite which form a brown stain on sand grains. In a few places the copper sulfides have been oxidized to azurite and malachite which occur as spots within the sandstone and as coatings on sand grains.

A sample of an ore roll surface marked by two parallel bands of clausthalite and an unknown mineral (fig. 9) was collected from the Firefly mine. An inner band, adjacent to the ore, is separated from an outer band by 5 to 10 mm of mineralized sandstone; both bands cut across the bedding. They separate barren to weakly mineralized sandstone from blue-black ore composed mainly of finely disseminated coffinite, montroseite, and corvusite. The isotopic analyses of the clausthalite agree with the analysis of galena in the Cashin mine as shown in table 2.

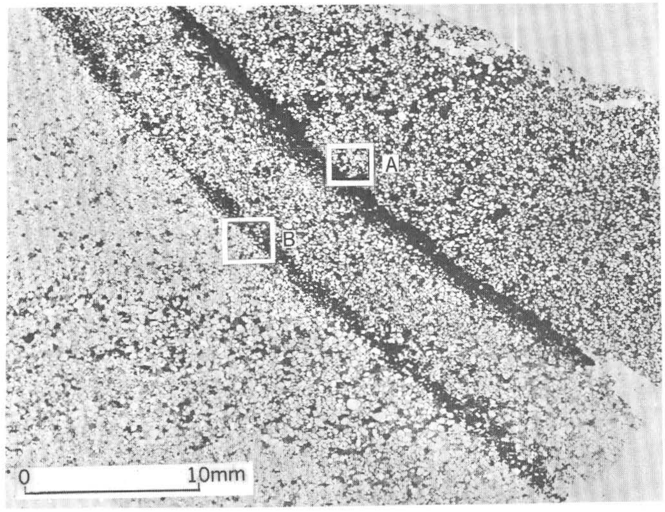



FIGURE 9.—Parallel bands of clausthalite and an unknown mineral along roll surface separating sandstone containing ore-grade material (upper right) from barren and sparsely mineralized sandstone (lower left). Sample WDC-148 from Firefly-Pigmay mine, San Juan County, Utah, collected by J. C. Warman. Letters refer to figure 10.

TABLE 2.—*Isotopic analyses of clausthalite and unknown lead-vanadium mineral from the Firefly-Pigmay mine and galena from the Cashin mine*

[Analyses: Firefly mine, by Union Carbide Nuclear Corp. Y-12 Plant, Oak Ridge Tenn. The values are believed to be correct to 0.5 percent. Cashin mine, by L. R. Stieff and T. W. Stern, U.S. Geological Survey, Washington, D.C. These values are believed to be correct to 1.0 percent]

| | $Pb^{204}$ | $Pb^{206}$ | $Pb^{207}$ | $Pb^{208}$ |
|---|---|---|---|---|
| Firefly mine: | | | | |
| Inner band unknown mineral. | 1.35 | 26.21 | 21.03 | 51.40 |
| Outer band clausthalite | 1.35 | 25.21 | 21.04 | 51.65 |
| Cashin mine: | | | | |
| Galena | 1.32 | 27.14 | 20.84 | 50.70 |

Steiff and Stern (written commun., 1956) state that the similarities of enrichment in radiogenic lead ($Pb^{206}$, $Pb^{207}$) relative to nonradiogenic lead ($Pb^{204}$) and the $Pb^{204}:Pb^{208}$ ratios with other such samples from the Colorado Plateau suggest that all are related in time (Tertiary) and possibly in source.

Spectrographic analyses of the two clausthalite bands show significant differences in composition (table 3).

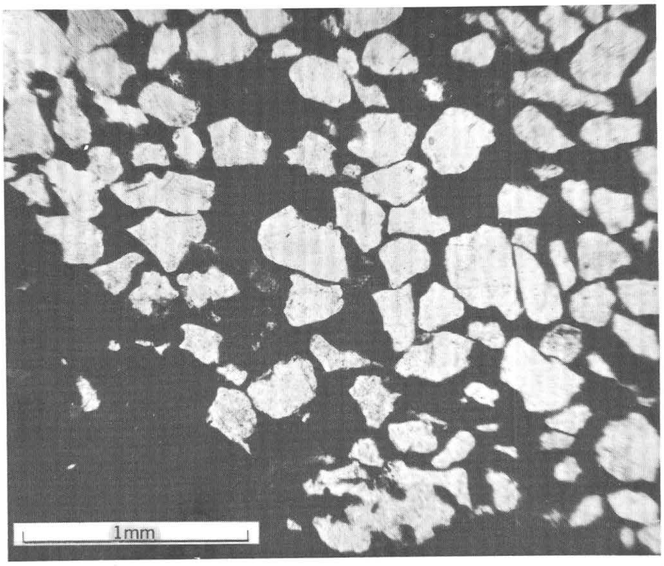
TABLE 3.—*Semiquantitative spectrographic analysis of clausthalite (outer band) and unknown lead-vanadium mineral (inner band) from the Firefly-Pigmay mine*

[Analyst, Mona Frank]

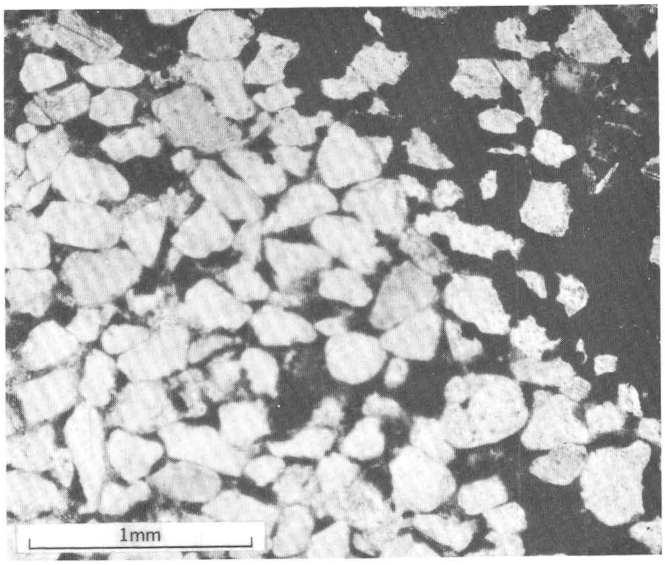
| *Content (percent)* | *Outer band* | *Inner band* |
|---|---|---|
| >10 | Pb, Si | Si, Pb |
| 5-10 | | |
| 1-5 | Se, Al | V, Al |
| .5-1 | V | Fe, K, Mg |
| .1-.5 | K, Fe, Mg | Ag, Cu |
| .05-.1 | Ag, Co, Cu, As | Ti, As |
| .01-.05 | Cr, B, Na, Ca, Ti, Mo | Ba, Ca, B, Sr, Co, Na |
| .005-.01 | Ba, Zr | Cr, Zn, Zr |
| .001-.005 | Mn, Sr | Mo, Be, Mn |
| .005-.001 | | Sc |

The most obvious difference in the element composition of the bands is that the outer contains selenium and the inner has none. The outer band also contains more lead. The inner band, on the other hand, is richer in silica, vanadium, iron, potassium, magnesium, silver, copper, and minor elements. The substitution of vanadium for selenium suggests that an unnamed lead-vanadium-silicate, resembling clausthalite in outward appearances, may be present. Comparison of photomicrographs shows that the quartz grains within the inner band (fig. 10*A*) are irregular in shape and widely separated and embayed by uranium and vanadium minerals. Traces of quartz grains, almost entirely corroded, are represented by pale shadows in the black areas. Outside the outer band (fig. 10*B*) the quartz grains are closely spaced and in shapes typical of ordinary sandstone. Embayments of the quartz grains occur along the edge and within the band. These relations indicate that the ore-bearing solution exsolved silica from quartz which, in turn, combined with lead, uranium, and vanadium to form the inner vanadium-rich lead-silicate band, coffinite, montroseite, and probably other uranium and vanadium silicates.

The unoxidized minerals, in general, appear to have formed at approximately the same time. In detail, however, pyrite and possibly some galena apparently formed first in decaying woody material. The woody material was then impregnated by uraninite and coffinite (fig. 11) which also appear to have corroded and filled embayments along the edges of the pyrite. Some of the pyrite was also replaced by other sulfides (fig. 11*B*), such as chalcocite, sphalerite, chalcopyrite, and covellite, but it is uncertain whether this replacement took place before, during, or after the emplacement of uranium. Table 4 summarizes the apparent paragenetic sequence of the minerals identified in the ore deposits of the La Sal Creek area.




*A*




*B*

FIGURE 10. Clausthalite bands in sandstone. Photomicrographs in plane light. *A*, Inner bands (dark area) showing corroded quartz grains (light) surrounded by unoxidized uranium-vanadium ore. *B*, Outer band, in barren to weakly mineralized sandstone; quartz grains (light) are corroded along margin of clausthalite band (dark area). See figure 9.

## ORIGIN

The genesis of uraniferous ore deposits in sedimentary rocks and especially of those in fluvial sandstone or conglomerate beds of the Colorado Plateau is highly controversial. Both syngenetic and epigenetic sources and under these a wide variety of hypotheses have been postulated as possible origins for these deposits. None, however, have been considered entirely satisfactory or unanimously accepted by students in this field. An excellent review of these various hypotheses and the problems that remain has been presented by McKelvey, Everhart, and Garrels (1955, p. 464–533; 1956, p. 41–53). They conclude that the Colorado Plateau and Witwatersrand deposits are epigenetic and were formed from deep-seated solutions probably emanating from igneous rocks that, for the most part, did not reach the surface.

Because studies in the La Sal quadrangle were limited in area and scope, the following discussion is limited to presenting field evidence, results of detailed studies, and ideas that have been formulated which either support or oppose the syngenetic and epigenetic hypotheses.

Any hypothesis of the origin of uranium-vanadium

TABLE 4.—*Apparent paragenetic sequence of uranium, vanadium, and accompanying sulfide minerals*

| Mineral | Sequence | |
| --- | --- | --- |
| | Unoxidized (primary?) | Oxidized (secondary?) |
| *Uranium minerals* | | |
| Boltwoodite(?) | | — |
| Carnotite ($U^{+6}$) | | ?——— |
| Coffinite ($U^{+4}$) | ?— | |
| Gummite | | ?— |
| Phosphuranylite | | — |
| Rauvite(?) ($U^{+6}$) | | — |
| Schroeckingerite(?) | | ?— |
| Saléeite-novacekite | | — |
| Torbernite (or meta-) | | ?— |
| Tyuyamunite (or meta) ($U^{+6}$) | | ?——— |
| Uraninite ($U^{+4}$) | ?— | |
| Uraninite (amorphous) | — | — |
| Uranophane | | —— |
| Beta-uranophane | | —— |
| Uranospathite | | —— |
| Metazeunerite | | — |
| *Vanadium minerals* | | |
| Corvusite ($V^{+4}$) | | — |
| Doloresite(?) ($V^{+4}$) | | — |
| Fervanite | | ——— |
| Hewettite ($V^{+5}$) | | ——— |
| Metahewettite ($V^{+5}$) | | —— |
| Hummerite(?) | | ——— |
| Melanovanadite | | —?— |
| Montroseite | — | |
| Paramontroseite | | — |
| Nolanite(?) | — | |
| Pascoite ($V^{+5}$) | | —— |
| Roscoelite ($V^{+3}$) | — | |
| Simplotite ($V^{+4}$) | | —?— |
| Vanadium hydromica ($V^{+3}$) | — | |
| *Accessory sulfide and selenide minerals* | | |
| Chalcocite | — | |
| Chalcopyrite | — | |
| Clausthalite | — | |
| Covellite | — | |
| Galena: | | |
| Nonradiogenic | — | |
| Radiogenic | —— | ——— |
| Pyrite | — | |
| Sphalerite | — | |
| Tennantite | — | |
| | Time ——→ | |

deposits in the La Sal quadrangle must take into account the following geologic evidence:

1. The areal distribution of uranium-vanadium deposits is restricted largely to defineable linear zones or belts that cross and appear to be independent of major tectonic features.
2. Most of the deposits show no obvious relation to local igneous rocks or to fissure veins which respectively could have served as source and conduits for hypogene solutions.
3. Uranium and vanadium minerals have not yet been found in veins cutting the igneous and sedimentary rocks of the La Sal Mountains, although veins carrying copper and lesser amounts of gold and silver have been mined.
4. Radon, however, has been reported by Hunt (1958, p. 356, 358) from the Dillon and McCoy adits of Mineral Mountain of the North Mountain group. Radioactivity in the igneous rocks is highest (about three times background) in the youngest intrusives (soda syenite porphyry) (Hunt, 1958, p. 338), but commercial deposits are lacking.

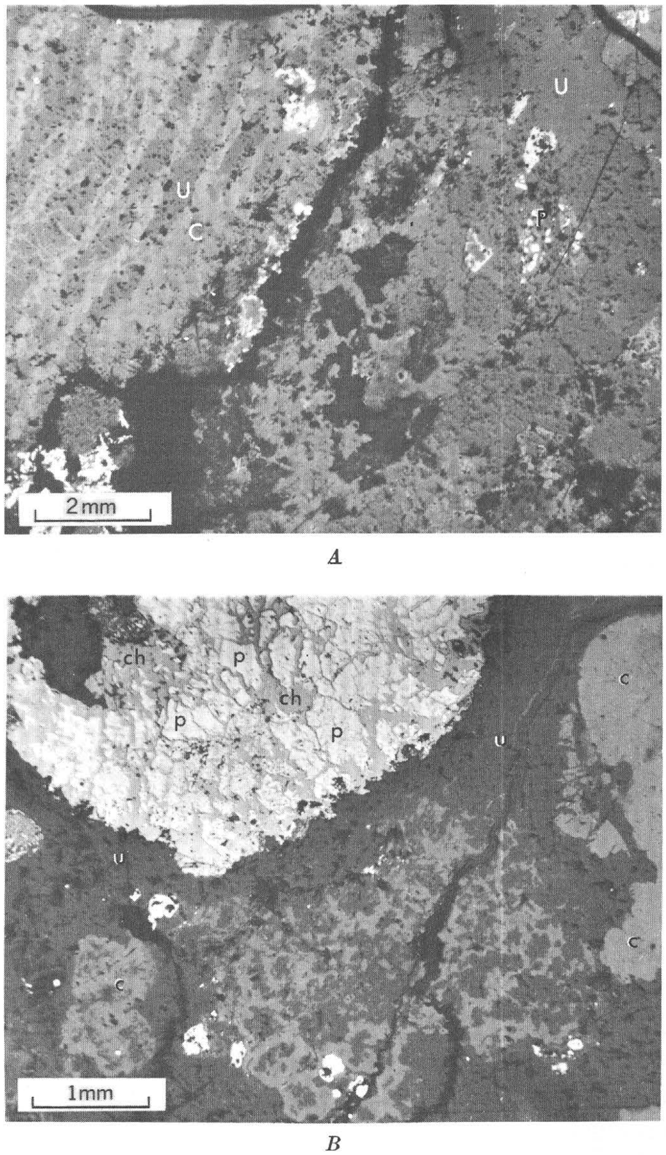



FIGURE 11.—Photomicrographs of a polished section of ore from the Gray Daun mine; specimen contains uraninite (u), coffinite (c), pyrite (p), and chalcocite (ch); galena, chalcopyrite and covellite are also present but not shown. *A*, Uraninite and coffinite replacing cellular structure of wood and surrounding corroded sulfide minerals. *B*, Pyrite replaced by chalcocite, embayed and surrounded by uraninite and coffinite.

5. The uranium-vanadium deposits are restricted stratigraphically to certain parts (paleochannels) of specific sandstone layers at the top of the Salt Wash Member and near the base of the Brushy Basin Member of the Morrison Formation.
6. The ore-bearing sandstone units are believed to have been derived from erosion of older rocks along

the southwest margin of the Colorado Plateau. These older rocks are largely granitic and contain hydrothermal veins of uraninite (Gruner, 1956).

7. The deposits consist of clusters of tabular, wedge-shaped, roll, and pod-shaped ore bodies enclosed in porous crossbedded sandstone lenses that are underlain, overlain, and interbedded by less permeable green mudstone layers, seams, and pellets.
8. Core sample, mine, and outcrop studies show that areas favorable for the occurrence of ore deposits are where the sandstone lenses are thickest (30 to 100 feet) and cleanest (white, light brown to light gray) and have little interstitial clay. Unfavorable areas are marked by thinner, finer grained sandstone permeated with reddish-brown interstitial clay.
9. Sandstone in favorable areas is permeable. Grain size varies locally and ranges from medium coarse to very fine. The average grain size is medium fine. In unfavorable areas, the sandstone is less permeable owing to finer grain size and the presence of interstitial clay.
10. Ore bodies are closely associated with and may contain carbonaceous material capable of creating a reducing environment. In places, ore minerals replace carbonaceous material; in other places, carbonate matrix is replaced. Corrosion of quartz grains has been noted.
11. Both oxidized and unoxidized uranium and vanadium minerals may comprise the deposits, and in places these minerals are associated with minor amounts of iron, copper, and lead sulfides and with traces of lead selenide.
12. Selenium has been noted in North Mountain by Hunt (1958, p. 338) who noted that it was most abundant in hydrothermally altered rocks having the highest content of copper, lead, and zinc. It was also found in the Firefly-Pigmay mine as clausthalite.
13. Age determinations based on ratios of radiogenic and nonradiogenic lead as well as $Pb^{206}:U^{238}$ ratios of uraninite indicate that the ore minerals formed during Late Cretaceous to early Tertiary time. Stratigraphic evidence and zircon age determinations indicate that the La Sal Mountains formed at the same time.

Paragraphs 1, 2, 3, and 6 above favor a syngenetic origin, whereas 4, 11, 12, and 13 favor an epigenetic process. The remaining four paragraphs (5, 7, 8, and 10) are amenable to both processes. This equal division of the evidence presented here suggests to the authors that the uranium-vanadium deposits were probably formed by a series of events employing both processes.

The distribution and localization of uranium deposits in the Plateau, and particularly those of the La Sal Creek mineral belt, appear to have been independent of tectonic structural features. The zonal or halo arrangement of deposits around laccolithic intrusives described by Reinhardt (1952) and Shoemaker (1954, written commun.) is, in the opinion of the authors, more apparent than real. Recent discoveries (1955) of uranium-vanadium ore in the Salt Wash Member west of La Sal Pass and on the east side of Mount Mellenthin show that the deposits near igneous rock are almost the same in mineral content, physical characteristics, and stratigraphic position as deposits farther away. The authors believe that the postulated zonal arrangement merely reflects the fact that in most places around the La Sal Mountains the ore-bearing strata are either deeply buried by Cretaceous and younger sedimentary rocks or, where they crop out, are poorly exposed; because of this sparsity of exposures, ore deposits appear widely separated. Physical conditions making access difficult have been a major deterrent to prospecting and exploration on the mountain flanks. Several exposures of the Salt Wash ore-bearing sandstone found in mapping the mountain region indicate that there may be several other favorable areas similar in orientation and areal extent to that of the La Sal Creek mineral belt.

The almost complete absence of hydrothermally altered material in the sedimentary rocks surrounding the dioritic rocks of the La Sal Mountains, which are believed genetically related in time to the uranium and copper ores, indicates that most of the magma was highly viscous and probably lacked volatiles. The fact that contact metamorphism is restricted to narrow zones around the igneous rocks indicates that the temperature of the magma was low but somewhat greater than that of the surrounding rocks. Evidence of hydrothermal alteration around the ore deposits is either lacking or has not yet been recognized. Estimates of the geothermal gradient based on information compiled by Hodgman and others (1955, p. 3088) indicate that prior to uplift and erosion the ore-bearing sandstone of the Salt Wash was covered by about 7,000 feet of rock and probably had a minimum temperature of 46°C. The ore zones of the Chinle Formation were covered by about 9,000 feet of rocks and probably had a temperature of at least 60°C. McKelvey and others (1956, p. 46) believe that host-rock temperatures may have been as high as 120°C, and pressures from 200 (hydrostatic load) to 800 atmospheres (lithostatic load) at the time the uranium-vanadium deposits were formed. Although these temperature estimates are admittedly crude, they are, according to Bateman (1951, p. 101) and others, within the lowest temperature range (50°C) of water that is commonly considered to be hydrothermal. It is probable that igneous intrusion and pressure of tectonic forces increased the temperature of the stratified rocks and connate water into ranges that are considered hydrothermal. Such a process may explain the presence of certain sulfide minerals in uranium-vanadium deposits that are believed to have formed at temperatures as high as 158°C (R. C. Coleman, oral commun., 1955). The absence of the alteration products commonly found in low-temperature hydrothermal veins, with the exception of kaolinite and chlorite noted in some uranium deposits, suggests that the temperatures of the host rock, intrastratal solution, and ore-bearing solution (if these two solutions were separate) were approximately the same. Thus, temperatures due to the depth of burial and perhaps slightly raised by tectonic forces may have played an important role in the mineralizing process, as indicated by the presence of certain metallic sulfides in deposits of both the Chinle and Morrison Formations of the Colorado Plateau. The authors believe, therefore, that uraniferous deposits of the plateau may have been "hydrothermal" only in the sense that, at the time the deposits were formed, the temperatures of the water-saturated sedimentary rocks were in the ranges ascribed as hydrothermal.

Hypogene solutions may also have been active in the area at this time. They probably rose along the earliest faults which formed as a result of tensional stresses during folding. The minerals believed to be derived from such solutions appear to be restricted to fault zones and associated fracture zones that are rarely more than 30 feet wide. Several of the major faults in and near the mapped area have brecciated zones containing minable deposits of argentiferous copper. The most notable of these is the Cashin Copper mine, 3 miles east of the La Sal quadrangle, which contains cuprous sulfides in the Wingate and native silver in the underlying Chinle Formation. The ore minerals generally occur as vein fillings, but, in places, chalcopyrite has replaced the sandstone host rock (Fischer, 1936, p. 572).

Samples of galena from the Cashin vein were analyzed by L. R. Stieff and T. W. Stern (written commun., 1956) who state that the isotopic compositions (that is, radiogenic and nonradiogenic lead) are present as follows:

| *Isotope* | *Atom percent* |
|---|---|
| $Pb^{204}$ | 1.32 |
| $Pb^{206}$ | 27.14 |
| $Pb^{207}$ | 20.84 |
| $Pb^{208}$ | 50.70 |

This analysis shows that the sample is substantially enriched in $Pb^{206}$ and $Pb^{207}$ and has a ratio of $Pb^{204}$ to $Pb^{208}$ similar to that of most of the Colorado Plateau galena samples. On the basis of this evidence Stieff and Stern reason that the lead in the sample is related in origin to that in other samples occurring in the uranium ores in the Triassic and Jurassic formations.

The $Pb^{206}:U^{238}$ ratio of a sample of uraninite and coffinite from the Gray Daun mine collected by Rasor (1952, p. 89–90) was also analyzed by Stieff and Stern (written commun., 1956). They state that "the age is 65 million years and is believed to be correct within 10 percent of the true age of the uraninite. This agrees well with other ages on superior material from the plateau."

These age determinations are not incompatible with those derived by H. W. Jaffe in the study of zircon contained in the porphyry masses of the La Sal Mountains or with structural and stratigraphic relations observed in the mapped area. It appears, therefore, that the dioritic phase of the laccolithic intrusion, regional folding and faulting, and the crystallization of quadrivalent uranium in the Morrison Formation and of sulfides in nearby vein deposits were contemporaneous and probably took place in Late Cretaceous or early Tertiary time. This evidence and the presence of similar accessory minerals in both the uranium and copper deposits lend greatest support to a hypogene origin but fail to explain, at least locally, the absence of uranium and vanadium in the nearby argentiferous copper vein deposits. In 1956 the authors and Theodore Botinelly of the U.S. Geological Survey discovered minor amounts of radioactive material in carbonaceous matter, presumed to be asphaltite, associated with native silver in the lower workings of the Cashin mine. This occurrence may eventually shed some light on the problem of origin of the uranium.

Though the approximate time of crystallization of the uranium-vanadium and the argentiferous copper ores has been established, the source and nature of the transporting medium of both types of deposits are still obscure. McKelvey and others (1955, p. 505–509) have discussed this and other problems involved in considerable detail. They state that at the time of ore emplacement the formations that became mineralized were saturated with water. They also believe that the positions of deposits within ore-bearing strata indicate that the ore-transporting medium had a density approximately the same as that of the pore water. They further suggest that this medium could have been either a liquid or a dense gas such as $CO_2$. This reasoning seems to the present authors to preclude almost entirely the possibility that petroleum was a transporting agent. Because so little is known about the solvent properties of water, oil, and dense $CO_2$ in elevated temperatures and pressures, McKelvey and others (1955, p. 509) prefer to think that the elements concentrated in plateau deposits and elsewhere were transported by hydrothermal solutions derived from a hypogene source.

Although several important aspects of the problem of genesis have been ignored here, partly for the sake of brevity and partly because of lack of information within the mapped area, the authors believe that the following conclusions best satisfy the observed field relations.

The uranium apparently could have been syngenetic in the sense that it was derived from the same source as the rocks in which it is now contained. Gruner (1956, p. 512–513) has indicated the availability of uranium in granitic rocks, and the authors believe that such a source for plateau ore deposits is feasible. Precambrian granite has been exposed along the margins of the plateau at periodic intervals since the late Paleozoic, for several of the formations are derived directly from granite and many others are products of reworked sediments that had a granitic source area. During weathering and erosion of the granitic masses, surface waters dissolved uranium, which is extremely soluble and easily leached from such rocks by mildly acidic solutions (Hurley, 1950, p. 5; Brown and others, 1953, p. 1400). This dissolved uranium was carried in solution as the uranyl ion $(U^{+6}O_2)^{+2}$, or as uranyl sulfate, or as carbonate ionic complexes (Garrels and Christ, 1959). Although the pH of the solution may have varied slightly from time to time in response to additions of materials of different chemical composition, the ionic compounds probably remained dispersed within the waters. These same waters deposited and saturated the sediments that filled the continental basin which occupied the area now referred to as the Colorado Plateau.

Woody material decays quite rapidly on burial and gives off $H_2S$ (Gruner, 1956). This active decay creates a neutral or reducing environment, which appears to be reflected by the green mudstone or bleached zone surrounding the deposits. The bleached zone is probably the result of removal of $Fe_2O_3$ (McKelvey and others, 1955, p. 507). Uranyl ions dispersed throughout the static intrastratal solutions in concentrations ranging from 0.0002 to 2.0000 ppm (McKelvey and others, 1955, p. 467) may have been drawn into the reducing areas by electron attraction or differences in pH where they formed concentrations of 1,000 ppm and greater. The ions nearest the reducing area probably became absorbed in and adsorbed by the woody material which acted as centers of ion accretion. Those ions traveling greater distances were deposited along the margins of such centers. Locally, silica was dissolved from the surface of quartz grains composing the sandstone and combined with uranium and minor elements to form coffinite and other silicates.

It appears that the concentration process was extremely slow and that these ions may have remained in solution until Late Cretaceous time when crustal disturbances initiated folding and igneous intrusion that changed the physical and chemical environment of the solutions. Such a change may have elevated both temperature and pressure, and precipitated the uranium and associated metals. As folding took place, the connate water began circulating and roll surfaces formed at the interface between the mobile water and the water containing crystallizing ore minerals.

## MINES

In 1957 there were 27 mines in the La Sal quadrangle. Between 1939 and 1957 these produced a total of about 75,000 tons of uranium-vanadium ore. Records of production prior to 1939 are incomplete, but estimates and records from 1939 to 1944 indicate that a total of about 12,600 tons had been produced by 1945 (C. W. Livingston, 1945, written commun.). The ore was mined from deposits ranging in size from a few tons to 16,000 tons and had a combined average grade of 2.02 percent $V_2O_5$ and 0.32 percent $U_3O_8$. The grade of the ore differs from deposit to deposit. The $V_2O_5 : U_3O_8$ ratios range from 4:1 to 14:1 and average 6 parts $V_2O_5$ to 1 part $U_3O_8$ for the total ore produced.

Most of the mines described are on the benches bounding La Sal Creek canyon (pls. 1, 5) and are included in the La Sal Creek mineral belt. Eight isolated mined deposits lie outside the principal mining district but within the mapped area (pl. 5). The ore produced from these mines amounts to less than 5 percent of the total production. Most of the deposits are contained in the uppermost continuous sandstone layer of the Salt Wash Member of the Morrison Formation. Three deposits have been mined from a discontinuous lens above the ore-bearing sandstone within the Salt Wash Member and four deposits are in sandstone lenses contained in the Brushy Basin Member of the Morrison Formation. The latter deposits range from a few tons to 600 tons, have an average production of about 400 tons, and were the source of less than 2 percent of the total ore produced within the mapped area.

For convenient reference the mines are listed and described in alphabetical order rather than by size, area, or stratigraphic position. The geographic location, history of ownership, and production, if known, are included with a description of the workings and stratigraphic and structural relations of the deposits. The size, shape, and orientation of the ore bodies are discussed in relation to the features that appear to have controlled ore deposition. In some of the mines only the more conspicuous minerals are listed. In others, especially those mapped in detail, the minerals and their apparent genetic relationship are discussed. These discussions also include the average content and ratio of $V_2O_5:U_3O_8$ of the ore produced from each mine.

Eight of the larger mines which were related to or resulted from the exploration drilling program conducted by the U.S. Geological Survey were mapped in detail on a scale of 1 inch equals 20 feet (pls. 6–13). These mines were mapped by two-man teams using a modified tape and compass method similar to that described by Forrester (1946, p. 333–340). This method is rapid and especially useful in mines where rooms or drifts are too small for the use of larger surveying instruments. Vertical sections portraying the geologic features were constructed by mapping the geology of the wallrock and projecting it to the line of section.

### ANGLE MINE

The Angle mine, shown as the Confusion-Angle mine on the map, (pl. 1) is about 2 miles north of Colorado Highway 90 along the west rim of Lion Creek canyon in sec. 1, T. 47 N., R. 20 W., Montrose County, Colo. The claim is one of 26 claims known as the Gramlich Group, located on the north side of La Sal Creek canyon between Lion Creek and Ice Lake canyons. Most of this group of claims were staked between 1939 and 1941. C. W. Livingston (written commun., 1945) states that on June 19, 1941, an agreement and deed recorded in Book 304, page 36, at the County Recorder's office, Montrose County, Montrose, Colo., divides the ownership of the group between Sam V., Irene, and John W. Gramlich. The Angle claim was one of those deeded to Sam V. and Irene Gramlich, who later sold it to the U.S. Vanadium Corp.

The claim lies well within the limits of the area of favorable ground referred to in this report as the La Sal Creek mineral belt. The deposit is within and about 27 feet above the base of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. It consists of a small ore pod that extends from its exposure on the Lion Creek canyon rim in a westerly to northwesterly direction. The workings are an open trench and a drift about 100 feet long. The most recent working on the claim is an underground drift that extends into the southwest end of the claim from the inclined shaft of the nearby Wedge mine.

The ore is of the oxidized type and composed dominantly of vanadium hydromica and carnotite which are disseminated as coatings on sand grains and as fillings between them. In places these minerals appear to have replaced carbonaceous wood fragments. The ore produced thus far averaged 2.60 percent $V_2O_5$ and 0.70 percent $U_3O_8$, a ratio of about 4 : 1.

About 100 tons of ore has been mined from the Angle claim. A few more tons have apparently been removed from the claim through the workings of the Confusion and Wedge mines on adjacent claims.

### BLACK HAT MINE

The Black Hat mine (pl. 1) is 1 mile north of La Sal Creek and just west of the Utah-Colorado line in sec. 28, T. 28 S., R. 26 E., San Juan County, Utah. The claim was staked in 1952 by J. B. Crowley of Grand Junction, Colo., who, in 1954, sold it to the Hardly Able Mining Co. of Moab, Utah. In 1956 it was operated by the Blue Creek Mining Co. Access to the property is by truck road extending from Utah Highway 46; one road turns off the highway at the confluence of La Sal and Hop Creeks, passes by the Vanadium Queen mine, and winds across the north bench of the La Sal Creek canyon to the shaft, a distance of 2 miles; the other turns north 0.2 mile east of the State line and extends to the head of Lion Creek Canyon.

The deposit was discovered in the summer of 1953 through the diamond-drilling program conducted by the U.S. Geological Survey. The deposit was originally mined from a steeply inclined shaft, but in 1957 a drift was being driven from the rim. Core samples indicate that the ore is contained in the upper part of the ore-bearing sandstone of the Salt Wash Member. The ore-bearing sandstone ranges in thickness from 40 to 70 feet in the vicinity of the deposit. The ore zone occupies an interval between 25 and 40 feet above the base of the sandstone marked by an underlying layer of green mudstone ranging from 0 to 4 feet in thickness. In places, discontinuous green mudstone seams separate the individual sandstone lenses which comprise the ore-bearing sandstone unit. Drilling indicates that the deposit is composed of ore bodies that occur as flat tabular layers ranging from 0 to 5 feet in thickness. Several of the layers of ore locally occur close together and there a greater thickness can be mined.

The ore minerals are closely associated with carbonaceous wood fragments and green mudstone occurring as seams and pellets and filling the interstices between sand grains. Though the ore minerals have not been studied in detail, they appear to be of the unoxidized or slightly oxidized type which includes pitchblende, coffinite, montroseite, and some melanovanadite and corvusite. These minerals occur as disseminations within the sandstone and as replacements of carbonaceous material. The dark ore minerals and associated carbon impart a dark-gray to black color to the sandstone host rock. The ore produced through 1956 contained 2.18 percent $V_2O_5$ and 0.32 percent $U_3O_8$, a ratio of about 7 : 1.

#### BRUSHY BASIN NO. 1 MINE

The Brushy Basin No. 1 mine (pl. 5) is on the Utah-Colorado line in parts of sec. 28, T. 29 S., R. 26 E., San Juan County, Utah, and in an unsurveyed section in T. 6 N., R. 20 W., Montrose County, Colo. The claim was staked in 1952 by W. C. Weaver of Grand Junction, Colo. Ore was produced in 1953 by the Great Western Uranium Corp. of Moab, Utah. Access to the property is by a series of dry-weather truck trails connecting with Utah Highway 46 at the Pine Lodge Ranch and extending southeastward across Wray Mesa to the south bench where the road turns westward to the claim, a total distance of approximately 9.6 miles.

The workings consist of a single adit that is about 50 feet long and bears N. 65° W. from the portal which is on the west side of a dry wash. The deposit is in a thin discontinuous sandstone lens about 100 feet above the base of the Brushy Basin Member of the Morrison Formation. The lens consists of light-brown fine- to coarse-grained silty sandstone composed of quartz, variegated chert, and light-gray mudstone pebbles. Green mudstone layers surround the mineral-rich part of the lens. The ore minerals are oxidized and consist primarily of carnotite. The ore is associated with thin carbonaceous shale layers that are commonly less than 1 inch thick or is contained in a carbonate-rich siltstone layer that ranges from 0 to 2 feet in thickness. The ore layer appears to have had an average thickness of 4 inches, and production records indicate that it contained 1.57 percent $V_2O_5$ and 0.25 percent $U_3O_8$, a ratio of 6:1. The mine has been abandoned since 1954.

#### BRUSHY BASIN NO. 3 MINE

The Brushy Basin No. 3 mine (pl. 1) lies about 2,000 feet east of the Utah-Colorado line and the Brushy Basin No. 1 mine in unsurveyed sec. 10, T. 46 N., R. 20 W., Montrose County, Colo. It was located by W. C. Weaver of Grand Junction, Colo., in 1952. Ore was produced in 1953 by the Great Western Uranium Corp. of Moab, Utah. Access to the property is by the same route that was described for the Brushy Basin No. 1 mine.

The workings consist of a shallow open pit that trends approximately east and is 300 feet long and 175 feet wide. The deposit is in a fine-grained sandstone layer that is about 5 feet thick and is about 120 above the base of the Brushy Basin Member of the Morrison Formation. The ore layers average 1 foot or less in thickness and cover an area about 200 feet long and 75 feet wide. The ore is composed of carnotite, schroeckingerite(?), and vanadium clay minerals disseminated in sandstone. The average grade is 1.61 percent $V_2O_5$ and 0.21 percent $U_3O_8$, a ratio of 6:1. The mine was not operating in 1957.

#### CONFUSION MINE

The Confusion mine, shown as the Confusion-Angle mine on the map (pl. 1), in the southwest corner sec. 1, T. 47 N., R. 20 W., Montrose County, Colo., was originally staked in 1929 by L. J. Gramlich of Paradox, Colo., and is part of the group of claims acquired by S. V., Irene, and John W. Gramlich in 1941. As of 1957, it is the property of the Union Carbide Nuclear Corp., a subsidiary of Union Carbide and Carbon Corp. The mine is on the west rim of Lion Creek Canyon and is reached by a truck trail that extends north for a distance of 2 miles from Colorado Highway 90 at the Hall Ranch 1½ miles east of the Utah-Colorado line.

The workings consist of an open pit and two caved inclines connected to a network of underground drifts, part of which extend into the Angle claim to the north. The open pit, mined between 1942 and 1945, exposes ore for a length of 170 feet and a width of 40 to 60 feet (C. W. Livingston, written commun., 1945). The ore has been mined from two zones in the ore-bearing sandstone unit of the Salt Wash Member of the Morrison. The upper zone, in the open pit, lies above a thin bed of green mudstone about 30 feet above the base of the sandstone. The lower zone is in the lower 10 feet of the sandstone. About 2 feet of green mudstone underlies this sandstone. The lower zone was mined by the incline and drift method in 1953.

The ore bodies are tabular, gently rolling deposits ranging from 0 to 3 feet in thickness. The roll surfaces trend approximately N. 80° W. and were measurable along their respective axes for 30 feet or more. The ore is of the oxidized type and composed dominantly of carnotite and vanadium clay minerals which fill the interstices of the sandstone. The ore contains 2.13 percent $V_2O_5$ and 0.47 percent $U_3O_8$, a ratio of 4:1.

The Confusion mine was abandoned at the time this study was made. The deposit, however, is well within the La Sal Creek mineral belt, and projections of the ore deposit may extend westward into the region of the Wedge workings (pl. 1).

#### ELRAY MINE

The Elray mine (pls. 1, 5) is in sec. 30, T. 47 N., R. 19 W., Montrose County, Colo., on the bench at the east end of Wray Mesa which overlooks the south fork of Sharp Canyon. Access to the mine is by 9.2 miles of truck trail which connects with Utah Highway 46 at the Pine Lodge Ranch and extends southeastward across Wray Mesa. In 1956 the name and ownership were uncertain because the property had changed hands frequently and with each change came a new name. The deposit is believed to have been originally staked as the Lucky Strike No. 13 claim.

The workings are in the upper part of the Salt Wash Member of the Morrison Formation at the stratigraphic level of the ore-bearing sandstone. Here, however, and in the adjacent areas positive correlation is difficult because the ore-bearing sandstone is thin, discontinuous, and highly lenticular. The workings consist of a small opencut and an underground drift which extends on a bearing of S. 65° W. for a distance of 40 feet from the edge of the opencut.

The deposit was mined in an opencut from the edge of a lens of thin fine-grained sandstone which trends N. 40° E. and pinches out at the portal. The material mined in the underground drift consists of carnotite in a discontinuous carbonaceous shale seam 4 to 5 inches thick, near the top of a lense of green mudstone. The green mudstone lens is overlain by reddish-brown mudstone, shale, and siltstone. The mined material contained 1.20 percent $V_2O_5$ and 0.19 percent $U_3O_8$, a ratio of 6 : 1.

The deposit is within 1,000 feet of the projection of the Sharp Canyon fault, but there is no apparent relation between the two.

### EVENING STAR MINE

The Evening Star mine (pl. 6) is in unsurveyed sec. 11, NE cor., T. 47 N., R. 20 W., Montrose County, Colo., about 1 mile east of the Utah-Colorado line. Access to the mine is by a steep, winding dirt road that connects with Colorado Highway 90, 1.6 miles to the south. The Evening Star deposit was discovered by wagon drilling conducted by J. W. Gramlich who began production in 1950. During 1956 and 1957 it was leased and operated by the Four Corners Uranium Corp.

The ore deposit is in the upper part of the Salt Wash Member of the Morrison Formation, the relatively continuous sandstone unit previously referred to as the ore-bearing sandstone (p. 12). The unit is a medium- to fine-grained sandstone containing interstratified lenses of reddish-brown or green mudstone. At the mine the sandstone ranges in thickness from about 60 to 70 feet.

The mine is divided into two workings (pl. 6). The northeast workings (Incline No. 1) consist of an inclined shaft connected to several irregularly trending drifts which in places are broadened into rooms as much as 40 feet wide. The workings cover an area roughly 375 feet long and about 340 feet wide.

The southwest workings (Incline No. 2), are entered by a short incline and consist of a maze of meandering drifts and rooms that extend over an area 320 feet long and 240 feet wide. The extreme west end of the workings is a single drift that is inclined downward 20 feet below the main level. This area was being mined at the time the mine was mapped. Both workings are virtually free of ground water.

The sandstone in different parts of the mine varies from white to gray to brown. The brown sandstone contains abundant limonite. In places the limonite is conspicuous as spots or bands against the lighter colored sandstone. In both workings the sandstone is dominantly massive, but in a few places it is crossbedded and flat bedded. In places the sandstone grades laterally into siltstone.

Mudstone is abundant in both workings as undulating beds, lenses, seams, pebbles, and films. These separate the sandstone lenses as illustrated in the mine sections (pl. 6). Mudstone conglomerate is also abundant and some of it contains angular mudstone fragments arranged in an imbricate fashion that may indicate the direction of paleo-stream flow. The mudstone in the mine is almost everywhere gray or green, but red mudstone was found as a thin layer within a green mudstone layer in the northeast workings.

The dominant joints in the mine (pl. 6) strike about N. 80° E., dip steeply to the southeast, and are roughly parallel to the axis of the La Sal Creek syncline. Nowhere in the mine is there any evidence that ore deposition was affected by the joint system.

The ore bodies are typical Salt Wash deposits; they occur as pods, irregular shaped lenses, and as gently rolling, tabular layers. Ore rolls are numerous in both workings and have a dominant trend of about N. 40°–50° E. (pl. 6). In some places two or three layers of ore occur in the drift or room walls, but these layers generally merge within a short distance. It is thought that the deposit is made up of several extensive blanket-like layers, but because of their undulating nature it is difficult to ascertain their true extent or to separate them, even where they are well exposed in the workings. The pods and small lenses of ore are bodies of quite limited extent and are mainly associated with carbonaceous matter.

The deposit is above the water table and appears to be partly oxidized. Nevertheless, the ore is black or dark gray, and yellow minerals such as carnotite and tyuyamunite are notably sparse. The generally dark color of the ore is probably due to the greater than normal proportion of vanadium to uranium. The ore has a $V_2O_5 : U_3O_8$ ratio of 8 : 1 which may be due to removal of soluble uranium salts by the flushing action of circulating ground water. Vanadium hydromica appears to be the dominant ore mineral and occurs as a coating on sand grains and filling between them. Corvusite is less abundant and occurs in podlike masses surrounding carbonaceous debris. Where these pods are exposed to the air for a short time, pascoite and tyuyamunite form on the surface. The ore produced from the Evening Star mine between 1950 and 1956 contained 2.00 percent $V_2O_5$ and 0.24 percent $U_3O_8$.

Carbonaceous woody material is erratically distributed throughout the workings and most commonly occurs as trash pockets or pods, and as thin seams or films between sandstone laminae. Fossil logs and log impressions are few, but wherever they occur they either contain or are surrounded by ore minerals, usually both. The logs have an average orientation of N. 55° W.

#### FIREFLY-PIGMAY MINE

The Firefly-Pigmay mine (pl. 7) is in sec. 30, T. 28 S., R. 26 E., San Juan County, Utah, about 10 miles east of La Sal, Utah. The portal of the mine is at the head of La Sal Creek Canyon, about half a mile above the confluence of Twomile and La Sal Creeks. The mine was, as of 1957, owned and operated by the Stocks-Gramlich Corp. of Moab, Utah.

The Firefly-Pigmay deposit was discovered in 1952 through the exploration drilling program conducted by the U.S. Geological Survey. It is in the uppermost continuous sandstone unit of the Salt Wash Member of the Morrison Formation of Jurassic age. This sandstone unit, commonly referred to as the ore-bearing sandstone, is composed mainly of broad lenses of medium- to fine-grained light-gray and light-brown sandstone; it includes lenses of reddish-brown and green mudstone. In the vicinity of the mine the sandstone ranges in thickness from 30 to 90 feet. The deposit trends east and lies at the west end of the explored part of the La Sal Creek mineral belt. The deposit is oriented obliquely to the axis of the La Sal Creek syncline.

Contours drawn on the base of the ore-bearing sandstone show a nose, trending slightly west of north, that extends about 300 feet before dying out (fig. 7). West of the nose is a shallow depression in which the deposit is located. This nose is primarily a sedimentary feature that is independent of the tectonic structure, probably a cuspate spur projecting from the bank into the ancient stream channel. This relationship of the deposit to sedimentary and Late Jurassic erosional features is significant in that other deposits in the La Sal Creek area are similarly located.

Access to the deposit is by a 1,200-foot drift bearing N. 15°–20° W. (pl. 7). The drift extends into the deposit for about 250 feet on a bearing of N. 50° W. The largest workings are west of the main drift, and at the time of mapping extended through an area approximately 300 feet long by 200 feet wide.

For a distance of approximately 600 feet from the portal, a continuous massive to crossbedded sandstone lens is exposed (pl. 7, section *A–A′*). It ranges from brown and light brown to light gray, white, and light green. Some mudstone and mudstone conglomerate beds are interbedded with the sandstone. These mudstone units, some as much as 3 feet thick in some places, truncate the sandstone bedding, but in most places conform with the bedding. The mudstone is red; some is partly gray or mottled green. The sandstone unit in the drift is completely devoid of carbonaceous woody material. Limonite spots are common but not everywhere present in the sandstone.

Overlying the sandstone and intertonguing with it is a red mudstone unit that is exposed at a point 600 feet from the portal and extends along the drift for 420 feet (pl. 7, section *A′–A″*). Although predominantly red, the mudstone is mottled green in places and intertongues with gray mudstone. The red mudstone unit is overlain by a green mudstone layer, 1 to 2 feet thick, which is present at the back of the drift about 980 feet from the portal. The green layer dips northward along the drift for 140 feet where it enters the floor. About 1,020 feet from the portal the underlying red mudstone unit is sparsely mottled green. The green mottling increases farther inward so that at about 1,080 feet the two mudstone units appear to merge and form a single green layer that is 3 to 4 feet thick. Nodular gray limestone masses are all along the walls of the drift in this green mudstone unit.

The sandstone lens containing the Firefly deposit is first exposed in the back of the drift about 1,030 feet from the portal. It rests on the green mudstone layer described above. The basal contact of the sandstone dips northward and the dip is believed to define the edge of a broad channel having characteristics similar to those described by McKay (1955, p. 269–270). The sandstone is white to gray or light brown where limonite is abundant. The contact between it and the underlying mudstone is exposed for a distance of about 90 feet, and because the contact is undulatory, a scour and fill relationship is suggested. This sandstone unit is distinctly different and separate from the lens at the portal of the mine.

Beyond 1,120 feet from the portal the drift is in a sandstone unit that contains abundant mudstone conglomerate layers and lenses, especially in the back. Near the end of the drift a gray-green mudstone-siltstone unit overlying the ore-bearing sandstone lens extends from the back. About 2½ feet of this unit is exposed at the end of the drift. The undulatory bedding in the unit is probably the result of differential compaction rather than of scour and fill. Drill holes show that the total thickness of the sandstone unit is at least 85 feet. Appreciable quantities of carbonaceous woody material are present in the sandstone.

The channel sandstone lens that constitutes the ore-bearing unit is continuous from the area of the main drift into both of the west workings (pl. 7, section *C–C′* and *D–D′*). It is virtually the same in color, lithology, and thickness throughout the mine. Drill-hole data show that the upper 40 to 50 feet grades westward into a finer grained sandstone. Gray and green mudstone conglomerate and seams are abundant. Red mudstone is present but not abundant. Carbonaceous wood is more abundant in the west working than in the workings along the main drift.

Fractures are numerous within 200 feet of the portal. They strike northeast and dip steeply southeast. The strike is parallel to the outcrop of the sandstone along the La Sal Creek Canyon and may reflect incipient slump due to the deep erosion of the canyon and permeation of the underlying mudstone by ground water. Fractures in the main west workings strike N. 20°–30° W. (pl. 7) and dip vertical or nearly vertical to both northeast and southwest. These fractures may be the result of tensional stresses related to the formation of the La Sal Creek syncline. The fractures that cut through the ore bodies do not appear to have controlled the emplacement of the ore and appear to be later than the mineralization.

The ore bodies in the Firefly-Pigmay deposit are tabular or undulating layers as much as 3 feet thick and 50 feet long by 40 feet wide. Some of the ore is concentrated in pods or is disseminated in the sandstone as irregular concretionlike bodies a few millimeters to a few inches in diameter. Ore rolls (pl. 7) are not common along the main drift but are present in the western part of the mine.

All except one of the ore bodies of the Firefly-Pigmay deposit are made up of the black, partly oxidized uranium-vanadium minerals. The single exception is in the upper workings (pl. 7, section *D–D′*) above the main drift. There the ore minerals are in part the oxidized types, principally the potassium and calcium uranyl vanadates, carnotite and tyuyamunite. Minor amounts of corvusite and other less oxidized vanadium minerals are present. The presence of both oxidized and unoxidized ore bodies in the Firefly-Pigmany mine is the result of ground-water conditions that prevailed in the deposit prior to mining operations. The ore bodies in the lower level were below the water table and were not subjected to oxidation. The upper ore body, which is 20 to 30 feet higher than the lower ore bodies, is above the water table and has been subjected to oxidation. The two ore levels are separated by a thin layer of green mudstone-pebble conglomerate.

The partly oxidized ores of the deposit are dark olive green, greenish black, and black. The green color may be due to the presence of roscoelite or vanadium hydromica. The black minerals include sooty pitchblende or uraninite, coffinite, and montroseite. Corvusite and possibly lumsdenite, a low-valent vanadate, are also present in the ore.

Accessory minerals such as pyrite and possibly chalcopyrite are finely disseminated with uranium and vanadium minerals that have replaced carbonized wood but are rarely found in the mineralized sandstone of the deposits. Clausthalite (fig. 9), a lead selenide, and an unknown mineral were found as two parallel bands, each no more than 1 mm thick bounding the convex edge of an ore roll. On the concave side of the bands, uraninite, coffinite(?), and montroseite fill the interstices between quartz grains. The quartz grains are extremely irregular in shape and of much smaller size than those of the opposite side of the band. The quartz appears to have been replaced by the uranium-bearing medium, and the dissolved silica is apparently atomically bonded with uranium molecules to form the recently discovered uranium silicate, coffinite (Stieff and others, 1955). On the convex side of the bands the sandstone is virtually barren of ore and the quartz grains are more rounded and closely packed. A few fine-grained uranium-vanadium minerals fill the interstices but are much less abundant than on the other side of the bands. Fine-grained carbonate minerals, mostly calcite, cement the quartz grains. Overgrowths of authigenic silica were not observed on the quartz grains in the barren zone.

Other samples were collected in 1954 by A. D. Weeks and J. C. Warman through the courtesy of Mr. Gardner, the mine foreman. Weeks (written commun., 1957), states that, in one place in the mine, uraninite and low-valent vanadium minerals containing traces of tennantite had formed on the surface of a carbonaceous log. She noted saléeite-novacekite had formed where uraninite had begun to oxidize. Elsewhere in the mine, Weeks found pyrite, galena, amber-colored sphalerite, and coffinite formed around carbonaceous material. She concluded, from the samples studied, that the Firefly-Pigmay mine was the least oxidized of those in the La Sal Creek area.

The ore produced from the Firefly-Pigmay mine through 1956 continued 2.04 percent $V_2O_5$ and 0.35 percent $U_3O_8$ in a V:U ratio of approximately 6:1.

Localization of ore bodies within such features as crossbeds or in festoons as described by Roach and Thompson (1959) in the Peanut mine of the Monogram Mesa area, Colorado, has not been found in the Firefly-Pigmay deposit. The ore-bearing sandstone in and around the deposit is flat bedded to gently crossbedded and in places steeply crossbedded. Festoon laminae are rare and inconspicious. Where the ore bodies are in crossbedded sandstone, regardless of their sizes and shapes, they transect the crossbeds.

Carbonaceous woody material occurs in appreciable amounts in the ore-bearing sandstone at the Firefly-Pigmay mine. For the most part the carbonaceous wood occurs as discontinuous seams in the sandstone or with mudstone bodies. One log is replaced by calcite at its center and has a carbonaceous rim that is mineralized. It is in the ore-bearing sandstone along the main drift about 3 feet above where the sandstone lens occupies a small channel scour in the underlying green mudstone (pl. 7, section *A–A′*). In the western part of the mine, carbonaceous wood and plants occur in thin seams and disseminated in mudstone as well as accumulations or trash pockets. Most of the uranium-vanadium minerals associated with carbon are in the west workings. Several logs are mineralized and one that was 18 feet long and 12 inches in diameter was mined.

As pointed out in the section on localization (p. 41), the deposits of the La Sal Creek area appear to be localized where sedimentary troughs or lows are found. However, the controls of localization of the individual ore bodies within the deposits are, in places, more subtle. Trites and Chew (1955, p. 245–247), in discussing the Happy Jack mine in southeastern Utah, believe that the localization of ores in the sandstone depends upon the permeability of the sandstone and the amount of carbonized wood and plants in the sandstone. They consider beds of intermediate permeability, that is, those containing claystone and siltstone bodies and cement, as more favorable than beds of highly permeable sandstone containing little interstitial claystone and siltstone or cement. Although these categories of relative permeability were used in describing a Shinarump channel deposit, they are, with modifications, generally applicable to Salt Wash deposits. In the Firefly mine, for example, mudstone bodies are generally present throughout the ore-bearing unit (pl. 7, sections *A–A′* and *B–B′*), as contrasted to the barren sandstone unit at the portal. Although a general relation of permeability to ore is believed to exist, the position of any single ore body cannot be shown as attributable to this factor alone, with perhaps one exception—the oxidized body in the upper workings (pl. 7, section *D–D′*). This body is in an upper zone of the ore-bearing sandstone 20 to 30 feet above the main deposits; it lies upon or close above a green mudstone lens that is 2 feet thick. It is thought that the lens served as a shelf above which a solution of uranium-vanadium minerals was concentrated and later precipitated to form the deposit.

### GRAY DAUN MINE

The Gray Daun mine, which consists of two separate workings, an eastern and a western (pl. 8), is in sec. 30, T. 28 S., R. 26 E., San Juan County, Utah, about 10 miles east of La Sal, Utah. The deposit was discovered during the mining on the Little Peter claim to the north. The Gray Daun mine was owned and operated in 1957 by the Stocks-Gramlich Corp. and had been in production since 1949. The portals of the mine open on the southwest side of Twomile Creek, about half a mile above its confluence with La Sal Creek where an access road to the mine leaves Utah Highway 46.

The mine is in the uppermost continuous sandstone unit of the Salt Wash Member of the Morrison Formation of Jurassic age. In the vicinity of the mines this unit is composed mainly of broad lenses of medium- to fine-grained light-gray and light-brown sandstone containing interbedded lenses of reddish-brown and green mudstone. The sandstone ranges from 30 to 105 feet in thickness.

#### WESTERN WORKINGS

The western workings of the Gray Daun mine have two portals that are 40 feet apart, one roughly west of the other. The workings consist mainly of a single sinuous drift about 540 feet long extending south from the portals (pl. 8). Just inside the western portal is a room that is 20 feet wide and 40 feet long and has two short adjoining side drifts. Two other short side drifts extend from the main drift at points deeper in the workings. The workings are dry throughout.

The rocks exposed in the main drift of the workings are mostly light-brown to white sandstone that is massive or flat bedded to crossbedded. Mudstone lenses are common on the sandstone, mainly at the back or high on the walls of the drift. In places the lenses and beds of mudstone are contorted about rounded limonite sandstone masses as a result of either differential compaction or slump or possibly both. The mudstone units in the west workings are green or gray. In one place in the drift about 230 feet from the portal (pl. 8, section *A–A'*), the sandstone has been scoured and filled by another sandstone unit. The scour boundary is defined by a weakly mineralized mudstone-siltstone bed about 6 inches thick. The bed sweeps down from the back of the drift at an angle of 15° to 25°, dips eastward, and cuts across the entire exposed section of the original sandstone. The scour contact is exposed for a distance of 20 feet along the drift.

The fractures in the workings trend about N. 30° W. and dip steeply to the northeast. There appears to be no relationship between the fractures and the mineralized areas.

Uranium-vanadium minerals are sparse throughout the length of the drift and are rarely thick enough to be called ore. Thin undulating stringers of mineralized sandstone occur about 10 feet above the base of the ore-bearing unit. Where the sandstone unit has been scoured and filled, the ore minerals are in the thin mudstone-siltstone unit at the scour boundary and parallel to the bedding of the unit. There are two small isolated pockets of uranium-vanadium minerals and a mineralized log at the end of the drift. Carbonaceous wood fragments are sparse and dispersed as thin seams and films throughout the workings.

The eastern portal of the western workings opens into an irregular room about 50 feet long which once joined the west portal drift through a narrow opening which is now filled with gob. The sandstone exposed in the walls is similar in lithology to that in the rest of the workings. The ore occurs as a flat-lying tabular layer that terminates in a roll that was about 3 feet thick, 30 feet long, and 10 feet wide but which has been mined out. The roll axis is nearly straight and trends approximately 18° north of east. The roll is composed of black ore minerals, although they may be of the oxidized type.

#### EASTERN WORKINGS

The eastern workings are entered by four portals within a distance of 135 feet along the canyon wall. These portals join a maze of drifts and rooms. In plan the workings trend north-south and cover an area about 380 feet long and about 180 feet wide. The eastern workings are the older part of the mine and many of the drifts and stopes are partly filled with gob. The workings are entirely dry.

In the east workings the drift and stope walls are composed of white, light-gray, and light-brown sandstone that is both massive and bedded. No mudstone units of any substantial thickness are exposed in the drifts, although thin beds or lenses are common, especially at the back of the workings. In one place the mudstone has scalloped ripple bedding and contains sand-filled mud cracks that suggest deposition of fine-grained material alternating with periods of subaerial drying (pl. 8, section *A–A′*).

A few feet south of the mud cracks the mudstone is contorted around well-cemented sandstone that occurs in rounded boulder-sized masses. This feature may have resulted from slumping along the edge of a stream channel scour. As indicated in sections *A–A′* and *C–C′* (pl. 8), from the margin of this scour into the eastern section of the workings the ore is in progressively lower stratigraphic positions in the ore-bearing sandstone. This position is coincident with an increase in the continuity, thickness, and grade of these bodies. The marked difference in the ore bodies probably reflects a change in the nature of the ore-bearing sandstone. Contours drawn on the base of the sandstone from drilling data show a broad depression or channel in the area immediately behind the portals of the Gray Daun mine. Most of the tonnage produced thus far has been from the lower levels which are in this channellike feature.

The sparse mudstone and siltstone units exposed in the eastern workings are gray or green and occur chiefly as thin lenses or as thin, irregular units composed of mudstone fragments. The mudstone decreases the gross permeability of the ore-bearing sandstone and probably slowed the passage of ore-bearing solutions, but no direct relationship of mudstone units to ore bodies is recognized.

The dominant fractures are concentrated in the south half of the eastern workings and trend slightly west of north (pl. 8). The fractures are either vertical or dip steeply to the east and west; where they transect the ore bodies, they appear to postdate ore emplacement.

The ore in the eastern workings lies about 15 feet above the base of the ore-bearing sandstone in undulating or gently rolling tabular layers that range from 0 to 4 feet in thickness (pl. 8, section *C–C′*). Ore also occurs in irregular podlike accumulations as much as 3 inches in diameter that are grouped together along bedding planes (pl. 8, section *C–C′*) or occur as isolated bodies (pl. 8, section *A–A′*). In a few places the ore lies in clearly defined rolls that cut sharply across the sandstone bedding. One ore roll is S shaped in cross section. Almost all rolls trend about east parallel to the scour-and-fill structures mapped in the mine.

The uranium-vanadium minerals in the Gray Daun mine are mostly of the oxidized type. However, one of the first discoveries of pitchblende from sandstone-type deposits on the Colorado Plateau came from the Gray Daun mine (Rasor, 1952). Associated with pitchblende is carnotite, tyuyamunite, uranophane, torbernite, and phosphuranylite. Carnotite is the most abundant uranium ore mineral and is found in high-grade concentrations replacing logs and intimately associated with black minerals.

Montroseite, corvusite, hewettite, and metahewettite are present in vanadium-rich layers. The deposit appears nearly completely oxidized, probably because it is close to the canyon wall and lies above the present water table. The water table fell, no doubt, as Two-mile Creek cut through the ore-bearing sandstone.

Small patches or pods of partially unoxidized minerals remain in the lower part of the mine.

The principal minerals identified from the Gray Daun mine include carnotite, tyuyamunite, metatyuyamunite, gummite, corvusite, montroseite, a black uranium mineral that is probably coffinite, and vanadium hydromica (A. D. Weeks, oral commun., 1954). Also occuring in the Gray Daun mine are sparse amounts of pitchblende (uraninite) associated with the coffinite(?), and traces of selenium minerals (probably eucarite). Minor amounts of torbenite(?) and metatorbernite(?), phosphuranylite, uranophane, hewettite and metahewettite, and melanovanadate have been collected (Weeks, oral commun., 1954). Traces of the secondary copper minerals malachite and azurite have also been observed.

The ore produced from the Gray Daun mine contained 1.79 percent $V_2O_5$ and 0.39 percent $U_3O_8$, or a ratio of 5:1.

Carbonaceous wood is most abundant in the southern end of the eastern workings, and in several places this material is impregnated or partially replaced by uranium-vanadium minerals. These fragments of carbonaceous material appear to have served as centers about which the ore minerals were deposited. Although carbonaceous wood may have been a localizing material, not all ore bodies in the Gray Daun mine were localized in this way, for many of the ore bodies are devoid of such material. Conversely, not all the carbon fragments contain or are associated with ore minerals. It appears that mineralizing solutions must come in contact with carbon in order to precipitate the contained uranium and vanadium. In the south end of the long drift of the western workings, a carbonaceous log was mineralized, mostly by impregnation, whereas the enclosing sandstone is barren. Possibly such differences in mineralization lie in the relative concentrations of the mineralizing solutions reaching the different areas. The mineralizing process apparently was highly selective and was dependent on many factors.

#### HESPERUS MINE

The Hesperus mine (pl. 9) is in the NE. cor. sec. 32, T. 28 S., R. 26 E., San Juan County, Utah. It is about 11 miles east of La Sal, Utah. The mine portals are on the north side of La Sal Creek Canyon about 1 mile east of the confluence of La Sal and Twomile Creeks. Access to the mine is by a narrow truck trail which passes under the ore bin of the Vanadium Queen mine and continues in a southeasterly direction along the rim formed by the ore-bearing sandstone of the Salt Wash.

The deposit is in a discontinuous sandstone lens that ranges from 0 to 35 feet in thickness. Where exposed in the canyon wall it appears to lie above and is separate from the uppermost continuous sandstone unit—the ore-bearing sandstone of the Salt Wash—by mudstone layers that have a total thickness of 15 feet. This lens may extend into the ore-bearing sandstone north of the mine workings or it may pinch out.

The Hesperus mine is divided into two separate workings having eastern and western portals about 100 feet apart. The eastern workings are a single drift about 120 feet long. The western workings are composed of a drift that extends 75 feet from the portal. A side drift about 60 feet from the portal runs west and has branching drifts extending about 40 feet to the north.

The drift walls in both workings are in flat-bedded light-brown limonitic sandstone or white sandstone. Mudstone occurs in beds as much as 2 feet thick and is green to gray.

The fact that the fractures trend east, parallel to the canyon face, and dip steeply to the south suggests that they are the result of incipient slump of the beds along the rim of La Sal Creek Canyon.

The ore bodies generally are undulating blanketlike tabular layers as much as 1 foot thick, and more rarely they occur as isolated podlike bodies. They cover areas as much as 30 feet long and 10 feet wide and are composed of oxidized uranium and vanadium minerals that impregnate the sandstone and replace carbonaceous material. The advanced state of oxidation is probably due to the proximity of the ore deposit to the canyon wall. The principal uranium mineral is carnotite. Tyuyamunite occurs with the carnotite. Small amounts of corvusite were noted with pods of vanadium hydromica. Schroekingerite(?) is also present. The average grade of ore produced thus far is 1.57 percent $V_2O_5$ and 0.38 percent $U_3O_8$, a ratio of about 5:1.

Fragments of carbonized wood are abundant in the mine and occur as carbonaceous seams or are disseminated in mudstone or siltstone beds. One carbonized log was found in the workings but it is not mineralized.

The Hesperus deposit is one of three deposits in the La Sal Creek area that are unique in that they are in a sandstone lens that lies just above the main ore-bearing sandstone. The other two deposits, the Uranium Girl and the upper workings of the Maud mine, are on the south side of La Sal Creek Canyon within 7,000 feet of the Hesperus mine. All three deposits may lie within separate tongues of the ore-bearing sandstone, although possibly they are in a single narrow shoestringlike lens which, prior to erosion, was continuous through the area. This sandstone may represent the channel of a small distributory stream that flowed southeastward during the deposition of the uppermost Salt Wash. The close areal spacing of these deposits in this unit suggests a common origin.

### JACKPOT MINE

In 1913 W. W. Chiles and E. J. Reynolds located the Jackpot (pl. 5) claim near Buckeye Reservoir in sec. 2, T. 48 N., R. 20 W., Montrose County, Colo. It was restaked in 1939 and amended in 1953 by J. H. Coward. It was most recently operated by the Bee Hive Mining Co. which produced a few tons of ore during 1956. The property is reached from Paradox, Colo., by 11.8 miles of Forest Service road and truck trail which parallel West Paradox and Buckeye Creeks to Buckeye Reservoir. The road turns east at the west end of the reservoir crossing Buckeye Creek and continues to the mine just north of the lake.

The workings consist of a small open cut from which a drift extends N. 3° W. for 50 feet where it turns west along a fault plane which bears N. 60°–65° W. The extent of the workings along the fault is uncertain because the end of the workings has caved.

The deposit is in the Wingate Sandstone which is part of a large fault block within the Valley View fault complex. In the drift from the portal, two joint sets were noted, one striking N. 37° E. and dipping 74° NW. and the other trending N. 40° W. and dipping 86° SW. The ore mineral is principally carnotite; malachite and azurite are in the gangue. These minerals occur as spots in the sandstone along the fault and fractures. Submicroscopic dark minerals, presumed to be vanadium hydromica, occur in patches as disseminated crystals filling the interstices of the fine-grained sandstone.

The fact that the deposit is in a fault block of Wingate Sandstone and consists entirely of secondary oxidized minerals suggests to the authors that the deposit formed by the circulation of ground water that passed through nearby uranium-vanadium deposits within the Morrison Formation. The Salt Wash ore-bearing sandstone is not exposed in the immediate area and the area has not been explored by subsurface methods except for a few shallow drill holes within the fault zone. Subsurface exploration in areas either north or south of the mine might lead to the discovery of minable uranium-vanadium deposits in the ore-bearing sandstone of the Salt Wash.

The prospect has been worked periodically for many years and most recently in 1956 as a stripping operation. Production has been very limited. The ore contains 1.25 percent $V_2O_5$ and 0.14 percent $U_3O_8$, a ratio of 9:1. Material of ore grade is obtained by careful hand selection.

### LITTLE DON MINE

The Little Don mine (pl. 10) is in sec. 30, T. 28 S., R. 26 E., San Juan County, Utah. The portal of the mine is on the south side of Twomile Creek about half a mile above its confluence with La Sal Creek and about 700 feet southeast of the Gray Daun mine. A truck trail paralleling Twomile Creek provides access to the mine from Utah Highway 46. The mine was owned in 1957 by the Stocks-Gramlich Corp. of Moab, Utah, and was in operation during 1953 and 1954.

The Little Don deposit is in the lower part of the ore-bearing sandstone of the Salt Wash Member. This unit is composed mainly of broad lenses of medium- to fine-grained light-brown flat-bedded to crossbedded sandstone containing lenses of predominantly green mudstone. The sandstone at the mine ranges in thickness from 30 to 60 feet.

The mine workings are entered through two closely spaced portals, about 20 feet apart. These join and form a single sinuous drift bearing roughly S. 60° W. for about 200 feet. The mine is dry throughout.

The ore occurs as thin undulating seams or layers as much as 2 feet thick and as irregularly shaped accumulations in the sandstone. The largest body is about 35 feet long and 25 feet wide. The minerals are predominantly black and mostly are vanadium oxides, as reflected by a high $V_2O_5:U_3O_8$ ratio 12:1. The chief ore mineral, vanadium hydromica, coats sand grains and fills the interstices. Tyuyamunite, metatyuyamunite, and sparse amounts of carnotite are also present.

The high degree of oxidation indicated by the yellow minerals is probably due to the great number of fractures in the country rock and the proximity of the canyon wall. Production records show the ore contained 0.14 percent $U_3O_8$ and 1.71 percent $V_2O_5$.

Carbonized wood is very abundant throughout the mine. It occurs in the sandstone as seams and logs and as small fragments in mudstone. Although carbonaceous material and ore minerals occur in close proximity to each other, the carbonaceous material in many places is barren. In a few places in the mine the carbonaceous wood contains calcite, and in one place the wood is associated with limestone nodules in sandstone.

### LITTLE PETER MINE

The Little Peter mine (pl. 1) is on the north side of Twomile Creek in sec. 30, T. 28 S., R. 26 E., San Juan County, Utah. The claim was located on March 1, 1936, by Messrs. B. Stocks, J. Stocks, and M. J. Murphy (C. W. Livingston, written commun., 1945), and in 1956 was owned by the Stocks-Gramlich Corp. The property is reached by a truck trail that leaves Utah Highway 46 near the confluence of Twomile and La Sal Creeks and roughly parallels Twomile Creek for a distance of 1 mile.

The workings are in the lower part of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. They consist of about nine drifts that extend as much as 100 feet north from portals in the canyon wall. Some of the drifts are connected by cross drifts. The ore-bearing sandstone has an aggregate thickness of about 65 feet, but is divided in two parts by a green mudstone bed that ranges from 2 to 10 feet in thickness. The base of the mudstone layer is about 20 feet above the base of the sandstone.

The ore is in the lower sandstone lens near the mudstone. It occurs as thin discontinuous, gently rolling tabular layers and small pods associated with pockets of carbonaceous trash in and along bedding planes in sandstone. The long axes of two ore rolls and one mineral-replaced log trend N. 70° E. This trend is roughly parallel to sedimentary structures that indicate the direction of stream flow during deposition of the upper part of the Salt Wash. Both oxidized and unoxidized uranium and vanadium minerals occur in the ore. The layers, rolls, and pods contain finely disseminated uraninite(?), montroseite, and vanadium hydromica. Corvusite was noted in several small pods. Carnotite occurs in fossil logs in association with minor amounts of uraninite and as efflorescent coatings with pascoite, tyuyamunite, and fibrous gypsum on the surface of mineralized sandstone in the older workings.

Operation of the mine by the owners and several lessees has been intermittent, but small tonnages of ore have been produced annually since 1940. The average grade of the ore produced during the period is 1.31 percent $V_2O_5$ and 0.30 percent $U_3O_8$ in a ratio of 4:1.

### LUCKY NO. 1 MINE

The Lucky No. 1 mine (pl. 1) is in sec. 30, T. 47 N., R. 19 W., Montrose County, Colo. It is reached by a truck trail which leaves Utah Highway 46 at the Pine Lodge Ranch and crosses Wray Mesa to the bench at the head of Sharp Canyon, a distance of 9.4 miles. During 1953, Mr. H. N. Tidwell operated this mine.

The deposit is in a thin sandstone lens in the Brushy Basin Member of the Morrison Formation. The lens is as much as 4 feet thick and is about 70 feet above the ore-bearing sandstone of the Salt Wash Member. The beds dip 1° to 2° NE., toward the axis of the La Sal Creek syncline. The sandstone is composed of light-brown fine quartz grains spotted with limonite. The sandstone is interbedded with silty layers; it overlies thinly bedded variegated mudstone and is overlain by a partially bleached, platy layer of light-green mudstone that is 8 to 10 feet thick.

The workings consist of a single drift along the north side of the convex surface of a single ore roll which arches to the northwest and has an overall trend of N. 25° E. The roll is approximately 90 feet long and appears to have been about 4 feet wide and 3 feet thick along much of its length. The roll is displaced about 3 feet on the southwest end by a fault that trends N. 55° E. and dips 70° SE. The southeast side is downthrown and the drift inclines downward into the downthrown block a distance of about 20 feet. The exposed relations between the fault and ore indicate that the faulting occurred after the ore was in place. A very minor roll surface trending N. 50° E. was noted near the portal. It parallels the east end of the main ore roll.

The ore minerals are carnotite and a very fine grained, light greenish-gray to black vanadium mineral presumed to be vanadium hydromica. The gangue minerals are dominantly quartz and minor amounts of limonite, calcite, and possibly barite. Carbonate cement is abundant in the wall which forms the roll surface on which the ore rested. Carbonaceous material occurs as flakes on bedding planes but is not abundant.

### MARJORIE ANN MINE

The Marjorie Ann mine (pl. 11) is in unsurveyed sec. 11, T. 47 N., R. 20 W., about 1¼ miles east of the Utah-Colorado State line. The mine is reached by a dry-weather truck road that connects with Colorado Highway 90 2 miles to the south. The Marjorie Ann deposit was found during the course of a close-spaced diamond-drilling program conducted in the summer of 1952, by the U.S. Geological Survey.

The claim was staked as part of the Gramlich group in the name of Sam V., Irene, and John W. Gramlich. John W. Gramlich later acquired the property and in 1953 leased it to William Hall, Ray Maris, and Paul Killion. Their cooperation during the mine mapping was greatly appreciated by the authors. Production began early in 1954 and was mainly continuous into 1956. The property was purchased in 1956 by the Four Corners Uranium Corp.

The Marjorie Ann deposit is in the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. The ore-bearing sandstone in the vicinity of the deposit is more than 100 feet thick. The deposit occurs in the interval between 20 and 40 feet above the base of the sandstone.

The workings of the mine are reached by an incline having a 25 percent grade. It is about 170 feet long and bears S. 75° E. at the portal. The mine workings consist of a single large room supported by several pillars. The room is oriented north-south and is about 190 feet long and about 50 feet wide at the widest point. The mine is above the water table and usually dry except during the winter months.

The sandstone in which the deposit occurs is dominantly light brown but, in places, it is white or various shades of gray. The brown sandstone is permeated with limonite which occurs locally as small concretionary bodies or as spots called freckles. Crossbeds and ripple marks in sandstone lenses that overlie the ore indicate that the stream depositing the sandstone flowed southeastward. Scour features at the base of these lenses have a similar trend. In the ore layer, however, the bedding is obscure and the sandstone usually has a massive appearance. The direction of paleostream flow in this particular lens was, therefore, not positively established but appears to have been eastward.

The only large lens of mudstone in the workings is a thick red mudstone unit near the portal. The mudstone near the ore occurs as pellets and films or very fine fragments disseminated through the sandstone. Layers of mudstone conglomerate are rare. The mudstone near the ore bodies is green or gray, except for minor amounts of yellow and yellowish-brown mudstone. Grayish-black mudstone pellets found in one place are thought to be mineralized.

In the Marjorie Ann mine, uranium-vanadium minerals occur in undulating blanketlike layers (pl. 11, section *A–A′*) that are commonly too thin to be classed as ore. Most of the production has been from ore rolls, nine of which were discovered during mining. Most of the roll axes are straight, but one is curved and another splits into two divergent axes. In the latter, the roll formed a compound curved surface where the axis separates. The average direction of the axes of the rolls is about N. 85° E. (pl. 11).

Some of the ore is in a very friable limonitic sandstone unit that it 3 to 4 feet thick and contains abundant carbonaceous material. On casual inspection the sandstone unit does not appear mineralized, but close scrutiny reveals that very finely disseminated carnotite occurs in the interstices. This deposit is probably the result of oxidation and subsequent migration of uranium-vanadium minerals from nearby ore layers and rolls, possibly through the action of downward-percolating surface waters. The ore produced in the Marjorie Ann mine averaged 0.26 percent $U_3O_8$ and 1.37 percent $V_2O_5$ in a ratio of 5 : 1.

Carbonaceous woody material is abundant in the host sandstone and occurs as disseminated fragments and as trash seams or pockets. It is commonly associated with or close to mineralized material but is not everywhere mineralized. Only one small fossil log or branch was found in the mine.

Fractures are so sparse in the Marjorie Ann mine that no truly representative trend was noted.

#### MAUD MINE

The Maud mine (pl. 1), in the center of sec. 14, T. 47 N., R. 20 W., Montrose County, Colo., has for many years been the property of the Vanadium Corp. of America. It is reached by leaving Utah Highway 46 at the head of La Sal Creek Canyon and traveling 3.8 miles along the truck trail, then turning north and traveling one-fourth mile to the Canyon rim.

The claim has been mined at three different levels, and the workings consist of several opencuts on the top of two sandstone lenses in the upper part of the Salt Wash Member of the Morrison Formation. The sandstone lenses form the surface of the bench overlooking La Sal Creek Canyon. Underground drifts at the base of the ore-bearing sandstone are reached by a portal in the reentrant east of the surface cuts.

The upper workings are in a thin sandstone lens that may be the same as the one containing the deposits at the Uranium Girl and Hesperus mines to the west. Erosion and cover make positive correlation of this lens uncertain. The deposit occurs in a light-green to white fine-grained silty sandstone that ranges from 0 to 35 feet in thickness. The ore is in thin tabular layers and small rolls, one of which trends N. 40° W. Although most of the mineralized material has been removed, the ore apparently consisted mainly of carnotite and vanadium hydromica disseminated in the sandstone.

The middle workings are in the top of the ore-bearing sandstone of the Salt Wash Member. They consist of a shallow open pit about 50 feet in diameter and two short exploratory drifts; one of the drifts bears N. 55° W. and the other S. 50° E. from the rear of the pit. Each drift is about 50 feet long and contains the most promising mineralized material in the mine. The mineralized material occurs as thin tabular, slightly undulating layers which range from 0 to 1 foot in thickness. In the northwest drift the ore lies between joints that parallel the walls. These joints may have, in part, controlled the localization of the ore. The principal ore minerals are carnotite, corvusite, montroseite, and vanadium hydromica.

The lower workings are 45 feet below the middle workings and at the base of the ore-bearing sandstone. They consist of several drifts and small gob-filled stopes extending westward from the portal. An inclined track on a wooden trestle was used to raise the ore from the portal of the lower workings up the cliff to the middle workings. The principal ore minerals are vanadium hydromica and carnotite which occur disseminated in sandstone layers 4 to 6 inches thick. Carbonaceous material is closely associated with the ore minerals. Limonite is abundant and occurs as spots staining the sand grains.

The mine appears to be out of ore; however, the seams and pellets of green mudstone within the thick sandstone back of the portal together with carbonaceous trash give a favorable picture of the surrounding area. Drilling indicates that the ore-bearing sandstone thins to the south, but favorable ground may extend to the west.

Complete records of production are not available for the Maud mine. Ore produced in 1953 contained 3.60 percent $V_2O_5$ and 0.50 percent $U_3O_8$ in a ratio of 7:1. This ore is presumed to have been mined from the upper and middle levels.

### MORNING STAR MINE

The Morning Star mine (pl. 1) is on the west rim of Lion Creek Canyon in sec. 12, T. 47 N., R. 20 W., Montrose County, Colo. The claim was originally located in 1913 by L. F. Gramlich of Paradox, Colo. In 1939 it was owned and operated by J. W. Gramlich who, by 1945, had mined nearly 5,000 tons of ore. From 1945 through 1953, only small tonnages were removed. In 1954 it was acquired and operated by the Four Corners Uranium Corp. of Grand Junction, Colo. The mine is reached by a truck trail that leaves Colorado Highway 90 at the Hall Ranch about 1.6 miles east of the Utah-Colorado line.

The workings consist of a large open pit bounded on the west by a series of underground drifts which, combined, cover an area 640 feet long and 140 feet wide. The deposit is in the upper part of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. Here the beds dip about 2½° S. toward the axis of the La Sal Creek syncline.

The ore occurs in elongate, gently rolling tabular bodies and in isolated pods in crossbedded sandstone in a zone about 40 to 50 feet above the base of the sandstone. In places, films, galls, and seams of green mudstone mark the crossbedding planes which bound the ore bodies. A continuous green mudstone layer ranging in thickness from 1 to 5 feet is 5 to 10 feet above the ore layer. The individual ore bodies are as much as 4 feet thick and the average thickness of ore is about 1 foot. The orientation of the long axes of the ore rolls is dominantly S. 60°–70° E. and parallel to the direction of paleostream flow, as determined by sedimentary structures which are well exposed in the floor of the open pit.

The ore is yellow and greenish gray to dark gray and is mainly vanadium hydromica and sparse amounts of carnotite. These minerals occur in layers of platy sandstone and as "rattlesnake ore" where bedding planes are farther apart. "Rattlesnake ore" has a spotty appearance because the ore minerals are irregularly disseminated through the interstices and coat the sand grains. Carbonaceous material occurs as films and small fragments along bedding planes and in trash pockets. The thickest ore is in close proximity to the carbonaceous trash pockets; this association appears to be a reflection of the texture of the sandstone, for here the sand grains are somewhat coarser, more poorly sorted, and less well bedded than elsewhere.

The Morning Star deposit is within the southern boundary of the La Sal Creek mineral belt. Drill-hole data indicate that the ore-bearing sandstone thins on a structural nose that separates the Morning Star deposit from the deposit on the Evening Star claim. The structural nose is presumed to represent a cusp which formed along the paleochannel margin; it projects northward into the Salt Wash stream channel under the Big Bug claim at the west end of the Morning Star claim. Favorable sandstone and ore of the Morning Star deposit may extend into the Moonlight and Birthday claims to the northwest.

Records of production show the ore has an average grade of 1.80 percent $V_2O_5$ and 0.13 percent of $U_3O_8$ in a ratio of 14:1.

### NEW YELLOW SPOT MINE

The New Yellow Spot mine (pl. 1) is in the southwest corner of sec. 6, T. 47 N., R. 19 W., Montrose County, Colo. It is reached by traveling 8.6 miles from Paradox, Colo., by way of the Buckeye Reservoir-Dugway road which climbs the northwest end of Paradox Valley and extends southeastward along the southwest rim to the mine. The deposits were discovered and located as the New Yellow Spot claim by John W. Gramlich. They are on the east side of Lion Creek Canyon opposite the Gramlich Group. In 1940 the claim was relocated as the New Yellow Spot No. 1 claim by John, Richard, Leonard, and A. M. Stocks (C. W. Livingston, written commun., 1945); the following year the Stocks added the New Yellow Spot No. 2 and 3 claims. Shortly afterward they sold the group of claims to the U.S. Vanadium Corp. (now the Union Carbide Nuclear Corp.), the present (1956) owner. Ore was produced between 1940 and 1944, and the mine has been idle since that time. Production records for that period indicate that the ore had an average content of 1.70 percent $V_2O_5$. The uranium content was not given (Livingston, written commun., 1945) but is estimated to have been about equal to that of the nearby Morning Star mine or about 0.13 percent $U_3O_8$, a ratio of 14:1.

The workings are a series of opencuts in an erosional remnant of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. Lower sandstone and shale beds of the Salt Wash form the surface of the surrounding area which is on the southwest flank of the

Paradox Valley anticline. The beds dip 2° to 3° SW. toward the axis of the La Sal Creek syncline. The dominant joint pattern trends N. 55° W., roughly parallel to the strike of the beds. A less conspicuous set of joints trends N. 65° E. All the joints dip at high angles.

The deposits occur in a thin-bedded platy and crossbedded limonitic sandstone lens resting on a massive crossbedded sandstone that is 25 feet thick and forms the base of the ore-bearing unit. The ore bodies are tabular blanketlike masses, and rolls and pods as much as 4 feet thick; they cover areas from 30 to 160 feet long and 1 to 20 feet wide. The size and configuration of the workings suggest that the major production came from roll-type ore bodies which trend approximately N. 80° E.

The ore minerals are carnotite and vanadium hydromica, which occur along bedding planes and are disseminated in the host sandstone. The "rattlesnake ore" typical of oxidized deposits is common. The ore appears to have been localized largely by bedding structures such as platy sandstone referred to as festoons (Knight, 1930). Seams of green mudstone occur near the ore and in a few places may have limited the migration of the mineral-bearing solutions.

### SUMNER MINE

The Sumner mine (pl. 1) is in unsurveyed sec. 2, T. 47 N., R. 20 W., Montrose County, Colo. The property was located in 1941 as part of the Gramlich group under the ownership of Sam V., Irene, and John W. Gramlich, who later sold it to the U.S. Vanadium Corp. The property is reached by 3 miles of truck trail that turns north from Colorado Highway 90 at the William Hall ranch, which is 1.6 miles east of the Utah-Colorado line.

The workings consist of a group of opencuts in the eroded surface of a light-gray medium-grained conglomeratic sandstone. The sandstone is composed largely of quartz grains. Pebbles of black, red, and green chert are scattered throughout or are in thin lenses 1 to 2 feet thick near the base of the sandstone. The unit is frequently referred to locally as the "Christmas tree conglomerate," and it marks the base of the Brushy Basin Member of the Morrison Formation. The conglomeratic sandstone is separated from the ore-bearing sandstone of the Salt Wash Member by mudstone and siltstone beds which have an aggregate thickness of 70 feet.

The deposit, a cluster of ore rolls, covers an area about 200 feet long and 100 feet wide. The rolls appear to have been less than 50 feet long and about 3 to 6 feet wide, and to have had an average ore thickness of about 1 foot. The long axes of the rolls trend roughly N. 75° E. As erosion and surface stripping have removed most of the ore, the relationship between the rolls is uncertain, but they appear to have been interconnected by thin tabular layers of ore minerals that impregnated the sandstone.

The ore minerals are vanadium rich, averaging 1.79 percent $V_2O_5$ (Livingston, written commun., 1945), and include vanadium hydromica, tyuyamunite, and metatyuyamunite. Uranium is sparse, averaging about 0.07 percent $U_3O_8$, and occurs as carnotite intermixed with the tyuyamunite which imparts a greenish cast to the ore. The ratio of $V_2O_5$ to $U_3O_8$ in the deposit is about 12:1.

### TOO HIGH MINE

The Too High mine (pl. 3) is on the southeast side of Wray Mesa in sec. 36, T. 47 N., R. 20 W., Montrose County, Colo. The mine is reached from Utah Highway 46 by a dry-weather truck trail that turns southeast at the Pine Lodge ranch and crosses Wray Mesa to the mine on the south bench, a distance of about 9 miles. The deposit was discovered in 1952 by William C. Weaver of Grand Junction, Colo. It was mined during 1953 and 1954 by the Great Western Uranium Corp. of Moab, Utah.

The deposit is near the crest of a low anticlinal structure, an extension of the Pine Ridge anticline. The beds dip 1° to 2° SE. toward Greasewood Canyon and the axis of the East Coyote syncline. The workings consist of an open pit about 350 feet long and 150 feet wide.

The deposit is in a light-green fine- to coarse-grained conglomeratic sandstone lens that is about 200 feet above the base of the Brushy Basin Member of the Morrison Formation. The sandstone lens ranges from 0 to 30 feet in thickness and is composed dominantly of quartz grains and abundant varicolored chert, light-green clay minerals, and carbonaceous trash. The chert is black, red, or green and ranges from sand size to pebbles 1 cm in diameter. The smaller chert grains are scattered throughout the quartz sand and the pebbles are generally concentrated in lenticular pods. Green mudstone is abundant and occurs as films, seams, and pebbles and also fills the interstices between sand grains.

The ore bodies occur as pods in the coarser lenses near the base of the sandstone. In places, the pods appear to be connected by thin layers of ore that impregnate the sandstone. The ore minerals are carnotite, tyuyamunite or metatyuyamunite, and vanadium hydromica associated with the carbonaceous wood fragments, carbonaceous mudstone, and green mudstone. The average ore contains 2.23 percent $V_2O_5$ and 0.34 percent $U_3O_8$ in a ratio of 7:1.

### URANIUM GIRL MINE

The Uranium Girl mine is near the west side of sec. 14, T. 47 N., R. 20 W., Montrose County, Colo. (pl. 1), on the south rim of La Sal Creek Canyon. It is reached by the Yellow Bird truck trail which leaves Utah Highway 46 at the head of La Sal Creek Canyon and extends eastward for 3.2 miles to where a road turns north to the property. The Uranium Girl mine was first called the Emergency claim and was originally located in 1949. It was relocated in 1951 by Robert B., Shirley V., James, and H. W. Lammert. It was again relocated in 1953 by E. B. Swanson who renamed it the Uranium Girl and acquired quit claim deeds from previous owners.

The workings consist of a single opencut that covers an area approximately 75 feet long and 30 feet wide. The deposit is in a light-brown medium- to fine-grained sandstone lens that ranges from 0 to 30 feet in thickness and may be equivalent to the unit that contains the Hesperus mine and the uppermost workings of the Maud mine. This lens overlies about 35 feet of interbedded mudstone and sandstone which separate it from the ore-bearing sandstone of the Salt Wash Member. Recent (1954) drilling on the claim indicates that the ore-bearing sandstone is about 40 feet thick, is overlain and underlain by green mudstone layers, and contains green mudstone seams and pellets.

The ore minerals consist of carnotite and vanadium hydromica which are disseminated in thin layers of sandstone that range in thickness from 2 to 6 inches. In one place the mineralized material may have been 1 foot thick. Small pods containing carbonaceous trash and ore minerals are also present. The grade of the ore produced averages 1.95 percent $V_2O_5$ and 0.24 percent $U_3O_8$ in a ratio of 8 : 1.

### VALLEY VIEW MINE

The Valley View mine (pl. 1) is in sec. 7, T. 48 N., R. 19 W., Montrose County, Colo. The property includes a group of five claims, the Valley View, Valley View No. 2, Lucky Lode, Inspiration, and Inspiration No. 1, which were staked by Messrs. J. B. and R. J. Columbo and Robert Proctor of Paradox, Colo., between November 16, 1936, and June 10, 1940. The property was leased with option to purchase by U.S. Vanadium Corp. during 1941 and 1942, but after an unsuccessful program of exploration the property was returned to the original owners (Livingston, written commun., 1945). The claim was amended by Columbo on November 20, 1953. It has since been operated by the owners or on a lease basis by many different miners. In 1956 it was owned by the Price Exploration Co. of Grand Junction, Colo. The property is reached by the Carpenter Ridge Truck Trail from Paradox, Colo., a distance of 8 miles.

The mine workings are on the northeast flank of the Paradox anticline, just east of the Valley View fault. Here the brittle sandstones such as the Entrada have been sheared into thin blocks along the fault. The intercalated beds of sandstone and mudstone of formations such as the Morrison, however, have been abruptly upturned at a point of flexure that lies about 100 feet northeast of the fault trace. The more plastic shale layers separating the sandstone beds have been thinned by squeezing. The Morrison Formation is in contact with the Wingate, Kayenta, and Navajo Formations, which crop out on the southwest side of the fault.

The workings consist of seven adits, three of which lie northeast of the fault zone in an undisturbed, almost flat lying part of the ore-bearing sandstone unit of the Salt Wash Member. A few feet to the southwest of these workings the beds turn abruptly upward; dips range from 77° NE. to slightly overturned. In the upturned beds, ore has been mined from four different levels which are connected by winzes and raises. It is from these workings that the major part of the ore has been produced. The drifts bear N. 50° W., paralleling the strike of the upturned beds and the fault. The longest drift extends 580 feet, and along it are several overhead stopes. The vertical distance between the uppermost and lowermost workings is 140 feet.

The ore-bearing sandstone is about 30 feet thick and is composed largely of medium to fine quartz grains and minor amounts of chert and black opaque minerals. The upturned sandstone is well cemented by silica, iron oxides, and carbonates.

The ore bodies occur in the upper half of the sandstone and, aside from the fact that the beds are vertical, are typical of Salt Wash deposits. They occur as tabular sheets, pods, and rolls that range from 0 to 2 feet in thickness. The principal ore layers are localized between or near two seams of green mudstone which separate the sandstone lenses that compose the ore-bearing sandstone.

The ore minerals are carnotite, corvusite, montroseite, metatyuyamunite, and minor amounts of uraninite associated with carbonaceous logs, trash, and green mudstone. Carnotite and other oxidation products occur along slippage planes of minor faults and on fracture surfaces. The ore averages 1.34 percent $V_2O_5$ and 0.38 percent $U_3O_8$, a ratio of 4 : 1.

The similarities of the ore bodies in the Valley View deposit to other Salt Wash deposits, the high degree of cementation in the upturned part of the ore zone, and the absence of radioactive minerals along the principal fault plane in the vicinity of the Valley View mine indicate that the ore was present prior to movement along the Valley View fault. As discussed on page 34, the

Valley View fault may have formed during Late Cretaceous or early Tertiary time, possibly as the result of adjustment of the salt to compressional forces of the Laramide revolution. During this period of uplift, the formations on the southwest side of the fault were raised. The mass on the northeast side of the fault was left mainly intact, but the more plastic Morrison Formation was upturned as a result of drag along the fault. Later collapse of the salt mass initiated some downward movement of the beds on the southwest side of the fault, as shown by their present attitude, but it is doubtful that the formations lying to the northeast were disturbed to any great degree.

### VANADIUM QUEEN MINE

The Vanadium Queen mine (pl. 12) is in sec. 29, T. 28 S., R. 26 E., about 11 miles east of La Sal, Utah. The portals, on La Sal Creek Canyon about a third of a mile northeast of the confluence of La Sal and Twomile Creeks, are reached by a half mile of truck trail that connects with Utah State Highway 46 at the stream junction.

The Vanadium Queen claim was originally staked on July 16, 1931, by Messrs. L. H. Couchman and H. W. Balsley of Moab, Utah. The property was later acquired by Mr. Abe Day of Moab, Utah, who relocated the Vanadium Queen claim and staked 11 additional claims from a block 3,000 feet wide and 3,600 feet long. The Vanadium Queen Nos. 1–12 claims were drilled in the summer of 1953 by the U.S. Geological Survey. The mine workings, at that time, were those nearest the outcrop on the Vanadium Queen No. 1 claim. Mining activity had stopped because an exploratory drift bearing northeast penetrated a thick layer of dark-green mudstone that marked the edge of the ore-bearing sandstone lens.

Mining was resumed after the discovery of ore by drilling beyond the mudstone layer. In 1954 the property was sold to Mr. Don Danvers of San Antonio, Tex., and in 1955 it became the property of the Vanadium Queen Mining Corp., for whom Mr. Joe Pitts of Grand Junction, Colo.,was mine supervisor.

The Vanadium Queen deposit is in the uppermost continuous Salt Wash sandstone, commonly referred to as the ore-bearing sandstone (see p. 12). Drill-hole data from around the mine show that the ore-bearing sandstone ranges in thickness from 20 to 87 feet. In plan the group of deposits trend northeast and lie close to the axis of the La Sal Creek syncline but are oriented obliquely to it. The deposits extend along a low depression at the base of the ore-bearing sandstone. This depression is a sedimentary feature independent of tectonic structures and represents a local channel scoured by a Salt Wash stream into the underlying mudstone prior to deposition of the ore-bearing sandstone.

All three workings of the mine are connected by a single haulage drift. The main drift is about 550 feet long and varies in trend from N. 50° E. at the portal to about due north at the innermost workings.

The outer workings are the largest and oldest of the mine and are in the area around mine portals 1, 2, and 3. These workings comprise a maze of drifts and rooms that extend northwest and southeast of the main drift. Part of the workings are caved and were not mapped. The workings cover an area about 510 feet long and about 160 feet wide at its widest point and have an arcuate trend from northwest-southeast to northeast-southwest. The arcuate shape of the deposit and the trends of sedimentary features suggest that the deposit may be contained in a lenticular sandstone that was deposited in a channel meander.

The sandstone in the outer workings is light brown to light gray and consists of medium- to fine-grained quartz and minor accessory minerals. With the exception of the red and green mudstone at the portal and the dark-gray mudstone unit in the main drift (pl. 12, section *A–A′*) and in the east end of the working (pl. 12, section *B–B′*), mudstone is sparse and is limited chiefly to thin seams and films.

The dark-gray mudstone lens exposed in the main drift is considered important in reconstructing the order of sedimentation in the Vanadium Queen mine area and may be a factor affecting ore emplacement. Section *A–A′* (pl. 12), measured along the main haulageway, shows that the mudstone fills a scour cut in sandstone. This mudstone is also exposed farther east in the back of the middle workings where it overlies the same sandstone unit, but at a higher stratigraphic level. In the main haulageway the base of the mudstone swings downward toward the portal at an angle of 17°. The sandstone lens disappears in the floor of the drift and mudstone is exposed along the wall for a distance of 70 feet. The mudstone unit, in turn, is truncated on the west by another sandstone body. The mudstone lens may have been cut or scoured by a locally degrading stream, probably a stream at flood stage. This stream is marked by a small terrace that has been cut in the mudstone at the contact. These exposures indicate that at least five distinct episodes of sedimentation and scouring are recorded within this part of the mine: (1) deposition of the inner (middle workings) sandstone, (2) scour by stream action, (3) deposition of mudstone, (4) scour by stream action, and (5) deposition of outer (outer workings) sandstone.

The dark-gray mudstone exposed in the main drift also occurs near the back in the eastern end of the outer workings (pl. 12, section *B′–B″*) and in the middle workings. The basal contact of the mudstone is stratigraphically higher than in the main drift. The mudstone rests on a sandstone lens that is continuous with the deeply scoured sandstone of the middle workings. Both the sandstone unit and the gray mudstone overlying it have been scoured and are in contact with the same sandstone lens that truncates the gray mudstone in the main haulageway. The trend of the contact of this scour is indicated by the location of the edge of the gray mudstone (pl. 12).

Sedimentary features, such as crossbedding, ripple marks, and stream lineation (pl. 12), indicate that although the general channel direction was N. 70°–80° E., local meanders were widely divergent from the major trend. This same general channel direction was determined in the Firefly-Pigmay and Gray Daun mines and is confirmed by information from drill holes northeast of the Vanadium Queen mine.

The dark-gray mudstone may have been an impermeable barrier to mineral-rich solutions. If so, the solutions moving through the ore-bearing sandstone were deflected around the flanks or trapped by the mudstone lens. The elongate ore bodies and long axes of the ore rolls (pl. 12) generally parallel the margin of the mudstone lens and also the scour-and-fill features observed in the adjacent sandstone. Similar associations of mudstone lenses and ore bodies can be observed elsewhere in the mine.

The ore bodies of the outer workings occur as tabular blanketlike bodies and as pods and rolls. The blanket ore bodies are as much as 180 feet long and 80 feet wide. Some of the rolls are as much as 30 feet long. The ore in the outer workings is considerably oxidized and rich in disseminated carnotite, which with roscoelite and vanadium hydromica impart a greenish color to the ore. Roscoelite and vanadium hydromica are the principal vanadium minerals. The proximity of the deposits to the outcrop and their location above the water table explain the high degree of oxidation. Very sparse amounts of malachite and azurite occur as spots or "buttons" in one place on the drift walls. Carbonaceous wood is sparse in the outer workings where it occurs in barren mudstone. In a few places it occurs with mineralized material.

Most of the middle workings are east of the main drift and cover an area 130 feet long and 125 feet wide. It is almost entirely made up of rooms, pillars, and connecting drifts which join the main drift in two places. The middle workings are wet and require pumping.

The deposit mined in the middle workings is in a light gray to light brown massive to crossbedded sandstone lens containing minor amounts of mudstone. The mudstone occurs mostly as thin seams or lenses and is usually green or gray. In a few places, however, it is red. In the back over much of the working the dark-gray mudstone lens, described earlier, is exposed.

The ore in the middle workings occurs chiefly in undulating, tabular, or blanketlike bodies. The ore in some tabular bodies reaches a thickness of 6 feet or more. There are three short ore rolls, all 10 feet or less in length, in the workings. The ore is composed principally of black unoxidized and partially oxidized minerals. Apparently most of the ore bodies lay partly beneath the water table in a sandstone lens that was nearly enclosed by mudstone and partly saturated prior to mining. Sparse amounts of yellow minerals indicate that parts of the ore bodies were above the water table and partially oxidized.

In 1954 the ore body nearest the haulageway was sampled, shortly after it was first exposed, by A. D. Weeks and the authors. The ore below the track level was completely water saturated. Weeks (written commun., 1957) identified carnotite, tyuyamunite, metatyuyamunite, melanovanadite, simplotite, and vanadium silicates. She found that the water standing in the workings had a pH greater than 7.6. She believes the alkaline environment explains the presence of melanovanadite and simplotite, which form under such a condition. Weeks also noted the presence of a vanadium-iron mineral that gives an X-ray pattern similar to nolanite, which is a low-valent vanadium-iron mineral.

Carbonaceous wood is sparse in the middle workings, but where it is found ore minerals replace or impregnate it.

The innermost workings lie at the northeast end of the main drift, which is composed of rooms and connecting drifts covering an area about 100 feet long and 80 feet wide. Like the middle workings, the inner workings are wet, and places mined below the level of the main drift must be pumped.

The sandstone in the inner working is light brown to light gray, massive to crossbedded and, in places, is tightly cemented. A mudstone conglomerate layer 2 feet thick at the back just above the ore is exposed in the north and east walls of the working. A gray mudstone breccia lies near the margin of the ore body and below the conglomerate. The breccia apparently represents collapse of mudstone along the stream margin (fig. 12) during deposition of the ore-bearing sandstone. In places the angular mudstone fragments rest in an imbricate fashion within a broad shallow scour. In cross section, the degree of overlap shown by the fragments appears to indicate where individual fragments are with respect to the channel margin. Near the chan-

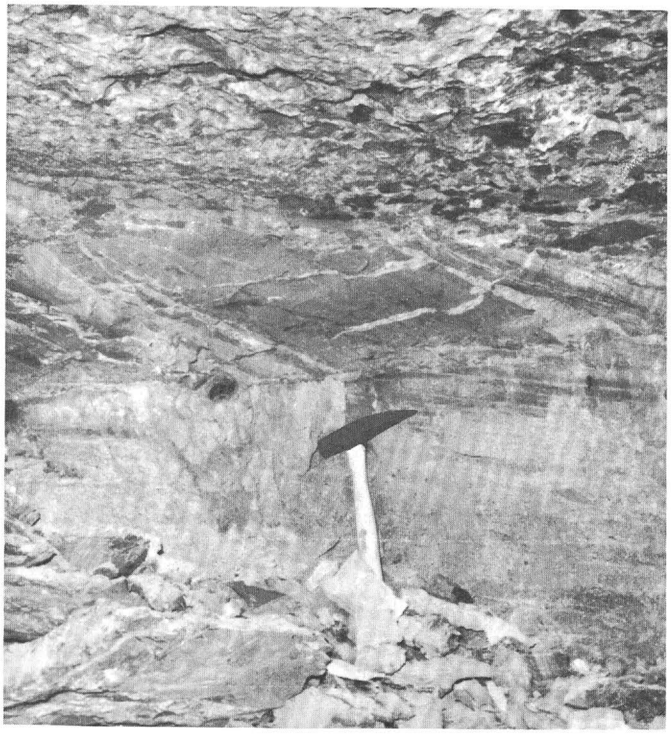


FIGURE 12.—Greenish-gray mudstone-pebble conglomerate (top) and mudstone breccia (middle) resting on ore-bearing sandstone lens in the Vanadium Queen mine.

nel axis, for example, overlap of the fragments is complete, and a line drawn along their edges will be almost vertical. On either side of the axis the fragments display overlap which increases laterally toward the channel margin, and the result is a shingling effect. A line drawn along the edges of overlapping fragments will be inclined toward the axis of the channel. Near the channel margins, overlap is slight, and lines drawn along the edges of overlapping fragments are only slightly inclined toward the channel axis. In the Vanadium Queen mine the local channel marked by mudstone fragments rests on a sandstone lens that contains ore. It is conceivable, therefore, that the study of imbricate mudstone breccias may be used locally as a guide to thicker sandstone lenses and, subsequently, to new ore bodies.

The ore of the inner workings occurs in undulating tabular or blanketlike bodies as much as 60 feet long, 50 feet wide, and 5 feet thick. Several small pods as much as 3 feet long occur in the workings. The ore is predominantly the black type but in places blue-black and yellow ore is found. The yellow carnotitetype ore is on or in close proximity to open fractures. The presence of blue-black minerals in the ore of the inner workings suggests that the ore bodies are in an initial stage of oxidation. As in the ore bodies of the middle workings, the oxidation state of these ore bodies is probably related to a relatively recent drop in the water table.

Carbonaceous wood is very sparse in the inner workings and is found as macerated debris on the bedding planes of the barren sandstone.

The principal vanadium minerals in the Vanadium Queen mine are montroseite, corvusite, vanadium hydromica, hewettite, tyuyamunite and simplotite. The principal uranium minerals are uraninite, coffinite(?), and carnotite. Most of the ore minerals coat the quartz grains, fill the interstices between them, and, in places, replace fossil wood. Montroseite, corvusite, pitchblende, and coffinite(?) are intimately intermixed in the ore bodies that are virtually unoxidized. The oxidized parts of the deposits contain the remainder of the mineral suite. The ore produced contains 2.79 percent $V_2O_5$ and 0.35 percent $U_3O_8$ in a ratio of 8:1.

There are two sets of fractures in the Vanadium Queen mine: a dominant set that trends N. 70° W. to due west, and a minor set that trends slightly west of north. The dominant set is best exposed in the main drift near the portal. This set roughly parallels the axis of the La Sal Creek syncline and is thought to be accentuated by incipient slumping of the beds near the canyon wall. The second set is nearly perpendicular to the axis and is thought to be the result of tensional stress. The fractures appear to have in no way controlled the deposition of the ore; however, where the fractures are open and penetrate the ore bodies, they have facilitated the circulation of ground water and the oxidation of the ore. Carnotite and tyuyamunite commonly coat the fracture surfaces.

### VISTA GRANDE MINE

The Vista Grande mine (pl. 1), in unsurveyed sec. 2, T. 47 N., R. 20 W., Montrose County, Colo., is reached by 2 miles of truck trail which turns north from Colorado Highway 90 at the William Hall ranch, 1½ miles east of the Utah-Colorado line. The claim was staked as part of the Gramlich Group by Sam V. and Irene Gramlich and has since been acquired by the U.S. Vanadium Corp. (now Union Carbide Nuclear Corp.).

The workings consist of a small opencut in the upper part of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation. The beds strike N. 65° W. and dip about 4° S. toward the axis of the La Sal Creek syncline.

Drill-hole data from the Vista Grande claim indicate that the ore-bearing sandstone ranges in thickness from 27 to 36 feet and is underlain by a layer of green mudstone that is 1 foot thick or less. The ground lies within the limits of the La Sal Creek mineral belt.

The ore bodies have been obscured by recent bulldozer operations, but they are assumed to be similar to those of the Confusion and Angle deposits nearby. In 1953 the mine produced ore that averaged 2.57 percent $V_2O_5$ and 0.44 percent $U_3O_8$, a ratio of 6:1.

### WEDGE MINE

The Wedge mine (pl. 1) is in the southeast corner of unsurveyed sec. 2, T. 47 N., R. 20 W., Montrose County, Colo. The Wedge claim was located in 1941 as part of the Gramlich group of 26 possessory claims which were staked by Sam V., Irene, and John W. Gramlich. On June 14, 1941, the group was divided and the Wedge claim became the property of Sam V. and Irene Gramlich, who later sold it to the U.S. Vanadium Corp., of Uravan, Colo. Company exploration by diamond drilling during 1951 and 1952 resulted in the discovery of ore under the Wedge and the Independence claim to the north. The mine was active during 1952 and 1953 when ore was produced from both claims.

The Wedge mine workings consist of an inclined shaft which bears N. 22° E. from the portal for about 150 feet where it is joined by a drift. This drift, bearing N. 35° E., extends for a distance of approximately 180 feet along the base of the ore-bearing sandstone of the Salt Wash. About 30 feet from the end a side drift, bearing N. 80° E., extends for a distance of 380 feet. There are small rooms adjoining the drifts.

The deposits are in the lower part of the ore-bearing sandstone, which within the claim ranges in thickness from 37 to 56 feet. The sandstone is underlain by a green mudstone layer that ranges from 0 to 3 feet in thickness. Mining has removed most of the ore, but it appears that the ore bodies were discontinuous pod-shaped masses rather than tabular layers and rolls. Abundant carbonized fragments of wood indicate that the pods were small trash pockets. The ore minerals are of the oxidized type and include carnotite, metatyuyamunite, and vanadium hydromica. These occur as coatings on quartz grains and as replacements of woody material. The carbon occurs as minute flakes in gray mudstone and as seams of shiny, black vitrainous material containing a minor amount of very fine grained marcasite. A few fragments of fossilized dinosaur bone were noted that are replaced largely by calcite and possibly by some barite. The ore produced had an average grade of 1.68 percent $V_2O_5$ and 0.38 percent $U_3O_8$, in a ratio of 4:1.

### YELLOW BIRD MINES

The Yellow Bird mines (pl. 13) are in secs. 13 and 14, T. 47 N., R. 20 W., Montrose County, Colo., approximately 1½ miles east of the Utah-Colorado line on the south side of La Sal Creek Canyon.

The mines are included in a group of claims owned and operated by the Vanadium Corp. of America, Durango, Colo. The four mine workings of the Yellow Bird group that have been mapped are on the Butterfly claim. Additional unmapped mine workings on the Eva and the Three Jacks claims, which lie east and west, respectively, of the Butterfly claim, are part of the Yellow Bird group. All the ore mined from these claims is listed under Yellow Bird. The claims are reached by a truck trail which leaves Utah Highway 46 near the top of the hill at the head of La Sal Creek Canyon and extends eastward along the north bench of Wray Mesa for a distance of 4½ miles.

The Yellow Bird mines have long been famous for their rich carnotite ore which was first mined in 1899 and used in concentration experiments at the Cashin Mill by Messrs. Poulot and Voillique. Ore from the Yellow Bird mines and the Rajah mine, of the Roc Creek area, was shipped to France where Madame Curie extracted radium. The remnants of a burro trail which traversed the canyon wall below the Yellow Bird mines serve as a reminder of those early days of uranium mining.

The Yellow Bird deposits are in the uppermost continuous sandstone of the Salt Wash Member of the Morrison Formation. The ore-bearing sandstone is about 50 to 110 feet thick in the vicinity of the mines and is composed of fine- to medium-grained light-brown to light-gray sandstone.

The mapped workings are along the canyon rim in a roughly east-west line extending a distance of about 700 feet. The westernmost consist of a single drift 110 feet long and 10 to 15 feet wide, trending S. 75° W. from the portal. The drift has one short adjoining side drift. The west middle workings, the smallest of the mines, consist of a wide drift that extends about 80 feet from the canyon rim S. 35° W. from the portal. In places the drift is as much as 20 feet wide. A short side drift adjoins the main drift near the portal.

The east middle working is a single room supported by several pillars. It is about 200 feet long and 95 feet wide at its widest point. In plan the workings have a "dog-leg" outline that trends S. 20° E. in the vicinity of the portal and S. 55° W. in the innermost part.

The easternmost workings are the largest and consist of several straight drifts that trend south from the canyon face and are connected by a sinuous cross drift. In places the drifts widen into rooms. The mine has two portals on the canyon rim that are about 50 feet apart. The mine workings cover an area 340 feet wide and 400 feet long. All the workings are virtually dry.

The sandstone is generally of the same character throughout the mine workings. It is mainly light brown to light gray, but locally where the sandstone is silty or contains abundant small mudstone lenses it is light green. The sandstone is crossbedded in places and, in other places, is nearly flat bedded or massive. Mudstone and siltstone are abundant in the ore-bearing sandstone and occur as thin seams or in layers as much as 4 feet thick and more rarely as thin conglomerate units. Some of the mudstone units display a "pinch-and-swell" structure. In section *G–G′* (pl. 13) where the lithology has been projected between the mapped sections, the mudstone cuts across the sandstone at an angle of 20°, a feature that suggests a scour-and-fill structure. In a few places the mudstone is contorted as a result of the slump of the immediately overlying sandstone beds. Nearly all mudstone and siltstone in the workings are gray or green.

The ore bodies of the Yellow Bird deposit are similar to those throughout the La Sal Creek area. They occur as gently rolling tabular layers as much as 170 feet long and 170 feet wide, and they range from 0 to 5 feet in thickness. Locally the ore occurs as discontinuous podlike bodies that are a few feet in length and less than a foot in thickness. Rolls are sparse in the mine workings. Only seven rolls were mapped; five of these bear northward between N. 30° W. and N. 30° E. (pl. 13). They range in length from 8 to 18 feet.

The ore of the Yellow Bird mine is generally dark gray to light greenish gray. The dominant ore minerals are vanadium hydromica, tyuyamunite, and carnotite which are most conspicuous near the east portal. In places, montroseite, corvusite, and pitchblende(?) are in small pods and thin layers that are generally dark gray, black, or bluish black in contrast with the other ores. The darker, less oxidized ores are in the rooms in the southern part of the east workings. The location of the light and dark minerals suggests that oxidation is greatest near the outcrop and progressively decreases away from it. The ore produced from the Yellow Bird mine contained 1.80 percent $V_2O_5$ and 0.34 percent $U^3O^8$, a ratio of 5:1.

Carbonaceous wood fragments and plant debris are sparse throughout the mine and only very few carbonaceous films occur in mineralized material. Two carbonaceous logs were found, a small barren log near ore and a larger mineralized log 30 feet long and as much as 1 foot in diameter. A few nonmineralized silica-replaced saurian bone fragments occur in the mine within ore layers.

Fractures in the mine workings trend generally N. 60°–80° W. (pl. 13) and have vertical or steep dips to the northeast. The fractures transect the ore bodies and nowhere appear to have had control over ore emplacement. In general, the fractures parallel the canyon rim and the axis of the La Sal Creek syncline. They appear to be accentuated by incipient slump along the canyon escarpment.

It is noteworthy that the Yellow Bird mines represent the only large accumulation of deposits on the south rim of La Sal Creek Canyon. The relation of the Yellow Bird deposits to the deposits on the north side of the canyon is obscured by erosion of the ore-bearing sandstone in the 4,000 feet of intervening canyon area that separates the Yellow Bird and Gramlich groups of mines. Data gained through mapping the Yellow Bird mines (pl. 13) and the mines north of the canyon (pls. 6, 12) indicate that the trends of the paleostream channels in the two areas are nearly normal to each other. The ore deposits north of the canyon are in a channel that trends generally east, whereas the Yellow Bird deposit is in what appears to be a north-trending channel. In the area west of the Yellow Bird mines, trends of sedimentary structures observed in rim exposures and in the lower workings of the Maud mine combined with drill-hole information from around the Uranium Girl mine indicate that a paleostream flowed along what is now the south edge of La Sal Creek Canyon. South of the Yellow Bird group, drilling showed that the ore-bearing sandstone consists of several relatively thin lenses separated by greater thicknesses of red mudstone. This suggests an "off-channel" or flood-plain area where streams depositing the Salt Wash flowed intermittently. By relating these areas to one another, it is postulated that a southern subsidiary channel branched from the main Salt Wash channel in the general area of the Firefly-Pigmay, Gray Daun, and Vanadium Queen mines and followed a more easterly course. This channel passed through an area that has since been eroded and is now the location of the present canyon. Only in the areas of the Uranium Girl, Maud, and Yellow Bird mines are vestiges of the paleochannel preserved. Trends of sedimentary structures in the Yellow Bird mine indicate that this subsidiary channel swung abruptly north in the area of the mine and perhaps rejoined the main channel in the vicinity of the Evening Star or Morning Star mines.

The ore rolls in the Yellow Bird mines display conspicuous parallelism to sedimentary structures (pl. 13) —such as current lineation, the dip of the crossbeds, and local stream scours. If the ore rolls were formed parallel to the movement of the mineralizing solutions as suggested by Shawe (1956, p. 239–241), then certainly the ore-bearing solutions followed the channels. This evidence and supporting evidence from other mines of the La Sal Creek area strongly indicate that the paleostream channels were the primary conduits through which the ore-bearing solutions moved and are the main sites in which ore is deposited.

### YIP YIP MINE

The Yip Yip mine (pl. 1) is on the south bench of Wray Mesa in unsurveyed sec. 1, T. 46 N., R. 20 W., Montrose County, Colo. The property was staked in 1951 by William C. Weaver. Access to the Yip Yip claims is gained by turning southeast from Utah Highway 46 at the Pine Lodge Ranch and crossing Wray Mesa on a dry-weather truck trail, for a distance of 8 miles. The mine was operated in 1952 and 1953 by the Don Danvers Uranium Co. of Moab, Utah.

The workings consist of an opencut along the ledge formed by the ore-bearing sandstone of the Salt Wash Member. An adit enters the base of the sandstone on the north side of the cut and extends 50 feet on a bearing N. 37° W. Near the end a second drift bearing N. 20° E. extends 60 feet, and along its northwest side are several small rooms. The portal is cut in a thin lens of light-brown thin-bedded silty sandstone that ranges from 0 to 5 feet in thickness. The sandstone is overlain by a green mudstone layer which separates the lens from other sandstone beds of the ore-bearing sandstone. The lens is composed of thin laminae of fine- to very fine grained well-sorted quartz grains. Limonite stain is abundant. The sandstone grades upward into platy carbonaceous siltstone which in turn grades upward into green mudstone. The carbonaceous siltstone contains the ore minerals; it ranges from 0 to 6 inches in thickness. Above the green mudstone layer is another silty carbonaceous unit similar to the one beneath the mudstone. Above this upper silty unit is highly crossbedded sandstone that is coarser grained than that at the base of the ore-bearing unit.

The deposit covers an area about 40 feet wide and 100 feet long. It consists of a single tabular ore body in the platy carbonaceous siltstone described earlier. Carnotite and vanadium hydromica appear to be the only ore minerals and are disseminated throughout the siltstone. The average grade of the material produced was 1.46 percent $V_2O_5$ and 0.34 percent $U_3O_8$ in a ratio of 4 : 1.

## SUGGESTIONS FOR PROSPECTING

The authors believe that several undiscovered deposits of uranium-vanadium exist in the La Sal quadrangle. The most favorable areas for these deposits will be discussed in the following paragraphs, in an order based on the amount of information available at the present time.

The area along La Sal Creek considered favorable (pl. 4) probably contains several deposits in addition to those now known. These may be found in the process of further defining the known deposits and the limits of the La Sal Creek mineral belt. Subsurface exploration between the Firefly and the Rattlesnake mine, west of La Sal, Utah, beyond the mapped area may disclose that the La Sal Creek mineral belt is virtually continuous to the west and contains deposits similar to those along La Sal Creek.

Other such belts may be present in the area and exploration around such deposits as those recently discovered on Hop Creek and the east flank of Mount Mellenthin may find favorable areas containing uranium-vanadium deposits. The area on Carpenter Ridge between the Valley View mine and the Lone Pine mine on Roc Creek, east of the mapped area is also considered to be worthy of drill exploration for uranium-vanadium deposits. The recent development of a deposit west of La Sal Pass, which is just west of the mapped area, and observed favorable thicknesses of the ore-bearing strata on Moore's Ridge and to the north suggest that the La Sal Pass area may contain deposits of uranium-vanadium ore. The fact that thick sandstone containing seams and pebble conglomerates of green mudstone crops out in the graben of the Scorup anticline along Geyser Creek suggests that this area may be favorable for uranium-vanadium deposits. West of the Valley View mine and Valley View fault are several prospects containing uranium-vanadium minerals. Where the ore-bearing sandstone is exposed it is more than 30 feet thick. Such thickness suggests that the area along the ridge east of West Paradox Creek and north of the National Forest boundary to Buckeye Reservoir may be underlain by ground favorable for uranium deposits.

In most of the areas discussed, surface prospecting will be extremely limited, for the ore-bearing sandstone is either poorly exposed or covered by younger sedimentary rocks or by rock debris and soil. In many places, the cover is many hundreds of feet thick. Much of the western part of the area is covered by debris from the igneous rock of the La Sal Mountains. Drilling will be difficult in fractured and faulted rock and in areas underlain by gravels composed of boulders of igneous rocks.

## GUIDES TO EXPLORATION AND ORE

Thickness of sandstone, its color and grain size, carbon and mudstone content, and sedimentary features such as scour-and-fill bedding, festoon bedding, and trash pockets (described on p. 43) were used in the process of searching for uranium-vanadium deposits by drilling and surface exploration. Various combinations of these features were used as criteria to determine whether the ground was favorable, semifavorable, or unfavorable for the presence of ore. For example, ground considered favorable is underlain by sandstone strata that are 30 feet or more thick; are light brown to light gray and of medium and fine grain size; contain sparse to abundant carbonaceous material and gray or grayish-green interstitial mudstone or mudstone as films, pebbles, or seams; and are underlain and (or) overlain by gray, greenish-gray, or green mudstone that is 0.1 foot or more thick. In contrast unfavorable ground is characterized by sandstone less than 30 feet thick or by complete absence of sandstone; if present, the sandstone is usually reddish brown, is composed of fine to very fine grains of sand and silt, contains no carbonaceous material, and is enclosed by reddish-brown mudstone above and below. Ground designated as semifavorable has a combination of favorable and unfavorable criteria as seen in a drill hole or vertical section of outcrop. These criteria were listed, and a scoring system similar to that described by Weir (1952, p. 23) was devised for ground classification. This system was revised as drilling progressed and more information was gained. A map showing the location of drill holes and ground classification was used concurrently with the drilling to determine the location of future drill holes (pl. 4). Supplemental maps such as contour maps of the base of the ore-bearing sandstone, isopachous maps showing thickness of the sandstone, isolithic maps showing ratio of sub-sand-size particles to sand-size particles in the sandstone, and maps showing areas underlain by green mudstone were also constructed from drill-hole data.

Geologic cross sections were constructed through completed drill holes to determine the most favorable coring interval for future drilling in unexplored ground. In explored ground, cross sections were used to show the relation to the ore-bearing sandstone to overlying and underlying strata and to correlate mineralized layers within the sandstone.

In general, these studies show that the ground designated as favorable (pl. 4) includes an irregular elongate belt bearing about N. 70° E. This belt roughly parallels the direction indicated by sedimentary structures. In this belt the ore-bearing sandstone is generally thickest, owing to scour-and-fill channels at the base of the sandstone and also to thickening at the top. North and south the sandstone lenses are thinner and interfinger with mudstone lenses.

The following summary of geologic features considered favorable for the presence of uranium-vanadium deposits is given to assist the search for additional deposits within the mapped area.

1. The host rock is composed of lenticular channel-type sandstone that is 30 feet thick or more. It is the uppermost continuous sandstone layer of the Salt Wash Member of the Morrison Formation.
2. The sandstone is light brown, white, or light gray.
3. The sand grains range from medium to fine (Wentworth scale) in size.
4. Green or gray mudstone is above or below the sandstone and within the sandstone as seams or pebbles, or it fills the interstices between sand grains.
5. Carbonaceous material is present as flakes or in trash pockets.

In addition to the basic features above, the following features may be helpful to the prospector at the outcrop or to the miner underground in determining the best direction in which to mine. Many of the ore bodies are known to parallel the direction of ancient Salt Wash stream flow. The measurement of the dip direction of bedding contacts and foreset bedding, the direction of current lineation on bedding surfaces, and local scour features may aid in determining this direction. Once determined, drilling along lines perpendicular to this direction or mining parallel to it with systematic crosscutting are accepted methods of exploration.

## OTHER RESOURCES OF POSSIBLE ECONOMIC INTEREST

### COAL

Deposits of low-rank bituminous coal in the La Sal quadrangle are mentioned here mainly because similar deposits in the Nucla-Naturita area to the east have been of local value to the uranium-vanadium industry and surrounding community. Thin seams, ranging from a few inches to three feet in thickness, are erratically distributed throughout the area in the middle member of the Dakota Sandstone of Late Cretaceous age. In much of the area, however, the middle and upper members of the Dakota have been removed by erosion, and only the lower conglomeratic sandstone member is left, especially in the southern third of the mapped area. To the north the Dakota has been preserved in entirety mainly in structural basins or in fault blocks associated with collapse.

The most notable occurrence of coal in the mapped area is at an abandoned mine in sec. 25, T. 48 N., R. 20 W., Montrose County, Colo., that is shown on Coffin's (1921) map as Mitchell's Coal mine (pl. 1). The deposit is at the head of Paradox Valley between the road from Paradox to Buckeye Reservoir and West Paradox Creek. The coal bed, as much as 2 feet thick, is in the upper part of the middle shale member of the Dakota, about 88 feet above the Burro Canyon-Dakota contact. The coal bed is in a sequence of gray carbonaceous mudstone and shale layers that total 110 feet in thickness. This sequence is capped by a yellowish-brown sandstone ledge 20 feet thick. The total thickness of the Dakota in this area is 147 feet.

The coal is generally dull black and has a brownish to black streak. Seamlets of a shiny black vitrainous material are very common. On weathered surfaces the bed disintegrates to small fragments and fine powder, but below the surface it forms shaly blocks which appear to be firm enough to withstand shipping. The ash content is high. Fusain or mineral charcoal is common. Specks of resin, common in other Cretaceous coals, are scattered through most of the unit. Minute flakes of marcasite and crystals of pyrite are present at many places.

One peculiar feature of the coal of the abandoned mine, which may be of academic interest only, is the abundant ellipsoidal cavities which resemble the casts of small pine cones. These cavities are of variable size but most are approximately 16 mm in length and 10 mm in diameter. The cavities are partly filled with a brown powdery fusainous substance which disintegrates to the touch and is therefore unidentifiable except that it is woody material of coniferous origin (R. W. Brown, written commun., 1956). Samples collected by J. C. Warman were studied by J. M. Schopf, U.S. Geological Survey, who states that, "the surface of the cast shows the cockscomb structure of marcasite which apparently crystallized during the peat stage of coalifaction, that is prior to compaction and consolidation. This time of crystallization prevented compaction of the organic matter encased by the marcasite. As crystallization progressed, the enclosed material became crushed and disorganized. After coalifaction the marcasite was, for the most part, leached out * * * and disorganized conical shapes which fit rather loosely in their casts were left. The cuticular material on the surface of the casts * * * has not suffered from vertical compression."

Other areas where coal beds of possible economic interest were noted were in secs. 14 and 17, T. 27 S., R. 25 E., and secs. 4 and 15, T. 28 S., R. 25 E., of San Juan County, Utah.

## COPPER DEPOSITS

Within the mapped area, copper minerals are in disseminated replacement deposits near the sedimentary-igneous contact and in fissures in sedimentary rock both near to and far from contacts with igneous rocks. None of the deposits is known to be of sufficient size or tenor to be classed as ore.

Minor concentrations of copper minerals were noted in rock dug from three caved prospect pits in sec. 31, T. 26 S., R. 25 E. (pl. 1), between Porcupine Ridge and North Mountain. The prospect pits are in beds belonging to either the Cutler or, more likely, the Rico Formation and lie within 300 to 800 feet of the igneous contact. The copper minerals are chalcopyrite and malachite that occur with more abundant amounts of pyrite. As far as determinable, the copper occurs in veinlets, probably filling fissures and replacing carbonate wallrock. Landslide material obscures much of the deposit and judgment was made on the basis of material in the prospect dump. However, a well-exposed deposit on the north side of North Mountain, outside the mapped area, is believed to be in a comparable geologic setting. This deposit is within 200 to 300 feet of the igneous contact and is composed of disseminated chalcopyrite and pyrite in minute veinlets in a gray limestone bed.

In sec. 14, T. 27 S., R. 24 E. (pl. 1), there is a copper deposit at the southwest end of a clastic dike. The clastic dike, described on page 30, is emplaced along a fault over most of its length, but is divergent from the fault near the deposit. A short exploratory drift that once gave access to the deposit is now caved, and talus covers much of the area. The copper occurs as chalcopyrite and malachite which are sparsely disseminated in the finely comminuted matrix material. No other metallic minerals were found associated with the copper.

The source of the copper in the limestone and clastic dike deposits is probably the same as the source of copper in the deposits in the igneous rock of North Mountain. Deep-seated hydrothermal solutions of late magmatic origin moved through the igneous rocks and precipitated copper minerals on contacting the carbonate beds of the enclosing sediments. Butler and others (1920, p. 161–162, 198) considered the La Sal and Henry Mountain copper deposits similar to those of the Beaver Lake district of Utah and considered them to be derived from solutions that were produced by differentiation in the magma reservoir.

North and northwest of Buckeye Reservoir, along the escarpment of the Valley View fault and its subsidiary faults, copper minerals, especially copper carbonates, are extensive but are not concentrated enough to be classed as ore. Several prospect pits and drifts reveal that chalcopyrite, azurite, and malachite are disseminated along fault planes and related fractures. In many places the copper carbonates occur as coatings and crystalline growths on the fracture surfaces, apparently independent of the copper sulfide minerals. Samples collected from a prospect near the Utah-Colorado State line west of Buckeye Reservoir contain a mineral that has been identified as crystalline malachite. It is a light-green acicular mineral commonly clustered in radial aggregates on fracture surfaces. Qualitative spectrographic analyses show that in addition to copper the mineral contains an unusual amount of vanadium.

It may include, therefore, some volborthite, a hydrous copper vanadate. Copper and uranium minerals are found in the Jackpot mine in sec. 2, T. 48 N., R. 20 W. (pl. 1). Both oxidized copper and uranium minerals are intermixed as coatings on fractures in the Wingate Sandstone.

The copper deposits along the Valley View fault are, in many respects, like the copper-bearing veins that Fischer (1936) described and thought to be of hypogene origin. The Valley View copper deposits have been modified by later oxidation processes. Evidence indicating the origin of these deposits is inconclusive. The fact that the deposits occur in part as sulfides and are emplaced in structures of tectonic origin suggests that they may be of hydrothermal origin. No other metallic sulfides have been found with the copper in the deposits of the Valley View fault complex within the mapped area.

Copper carbonate coats fault and joint surfaces at places that are a considerable distance from any known copper sulfide mineral; this relation suggests that recent oxidation and ground-water movement carried the copper from the places of original deposition and redeposited it at the present sites. This sequence of events appears to apply also to the associated uranium where it occurs only as the yellow oxidized minerals carnotite and tyuyamunite(?). These minerals are mostly in the form of incrustations or crystals on fracture surfaces of sandstone, in contrast to the more common occurrence as mineral grains and masses impregnating sandstone.

Where the Sharp Canyon fault passes through the northeast wall of La Sal Creek Canyon, east of the mapped area, several prospects in the Entrada Sandstone expose thin (less than ½ in. thick) veinlets of copper and iron sulfides, mostly chalcopyrite containing traces of bornite. If similarities with the Cashin, Sunrise, and other copper-bearing faults (Fischer, 1936) are consistent and continue at depth it is not improbable that deposits of argentiferous-copper ores occur near the base of the Wingate Sandstone, the zone in which such deposits were found in the other veins. The estimated depth to such deposits is about 420 feet where the Sharp Canyon fault crosses La Sal Creek in the adjacent Paradox quadrangle; however, at this location both surface and subsurface waters could create a major mining problem. Near the west wall of Spring Creek Canyon to the east, the depth to the base of the Wingate is estimated to be about 320 feet. These estimates are made on the assumption that normal thicknesses of the Kayenta and Wingate Formations are present in the area.

## IRON DEPOSITS

Deposits of iron-rich minerals are widely distributed within and around the margins of the igneous rock of the La Sal Mountains. Many of the deposits have been prospected, but none were being exploited in 1956.

Iron minerals mainly as specular hematite occur in at least six types of deposits: (1) as disseminated masses coating the joint surfaces in igneous rock, (2) as veins containing quartz and filling fractures in igneous rock, (3) as veinlets transecting sandstone, (4) as layers of disseminated minerals and in veinlets paralleling sandstone beds, (5) as minute botryoidal bodies and finely granular masses in the openings of sandstone breccia, and (6) as disseminations in lenses and as ovoid masses in metamorphosed shale. Hunt (1958, p. 335–336, 339) in his discussion of North Mountain notes the occurence of hematite in several environments and suggests that it was derived from the alteration of hornblende and other mafic minerals.

## OIL AND GAS

Numerous oil seeps and outcrops of bituminous sandstone have been known for many years in southwestern Colorado and southeastern Utah. Drilling in the Paradox Basin began in 1891 near Green River, Utah (Baker, 1933, p. 80), and has continued sporadically. Most of the exploratory wells were drilled on top or on the flanks of the salt anticlines and domes. A few holes were drilled in synclinal structures on the theory that, inasmuch as they are underlain by a thinner sequence of salt, the surface is much closer to the pre-Hermosa sedimentary rocks which may stand structurally higher there than under the adjacent anticlines.

The La Sal Mountain area lies within the Paradox Basin oil province, and all the formations containing producing horizons are represented in the stratigraphic section of the La Sal Mountain region. Although oil and gas associated with igneous and metamorphic rocks generally occur in quantities too small for commercial production, it might be well to consider the favorable aspects of the area. The La Sal Mountains can be considered as three separate domes, two of which are superimposed on elongate major anticlines. Smaller subsidiary structures are also superimposed on the anticlines near the mountains. These structures are higher in altitude than any of the structures producing oil or gas in the surrounding areas, and therefore, offer ideal conditions for the migration and accumulation of petroleum. As Hunt (1942, p. 197–203) points out, it is the doming of the sedimentary strata about the stocks of the laccolithic mountains that produces structure favorable for the entrapment of petroleum. Therefore, in spite of the fact that the Mesozoic and younger Paleozoic rocks have been breached where they arch over the laccoliths, there may be traps at depth in the older Paleozoic rocks.

## WATER

Water is of considerable importance within the La Sal quadrangle, for drinking, for the watering of stock and crops, and as a drilling medium in the exploration and mining of uranium-vanadium deposits.

The perennial streams include Taylor, Deep, Geyser, Twomile, Buckeye, West Paradox, and La Sal Creeks. Irrigation canals that connect Deep Creek to Geyser Creek and Geyser Creek to Buckeye Creek divert most of those drainages into Buckeye Reservoir which serves the farmlands in the northwest end of Paradox Valley. La Sal Creek is partly diverted by a canal which carries water to the village of La Sal and the surrounding farmland.

Numerous springs issue from the Burro Canyon Formation throughout most of the area. In La Sal Creek Canyon subsurface waters emerge from sandstone lenses in the Brushy Basin and Salt Wash Members of the Morrison Formation and the Entrada and Navajo Formations.

Artesian water supplied by large recharge areas in the La Sal Mountains and on the crests or flanks of the anticlines can be found in each of the above formations in certain areas. In exploring for uranium deposits by diamond drilling, several holes penetrated sandstone of the Morrison Formation which produced artesian water at depths ranging from 150 to 400 feet. A few of these wells have had an average output of 5 gallons per minute for more than 2½ years, have served as an excellent source of drinking water, and have provided a local water source for drilling projects.

## REFERENCES CITED

Baker, A.A., 1933, Geology and oil possiblities of the Moab district, Grand and San Juan Counties, Utah: U.S. Geol. Survey Bull. 841, 95 p.

——— 1946, Geology of the Green River Desert-Cataract Canyon region, Emery, Wayne, and Garfield Counties, Utah: U.S. Geol. Survey Bull. 951, 122 p.

Baker, A. A., Dane, C. H., Reeside, J. B., Jr., 1936, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico and Colorado: U.S. Geol. Survey Prof. Paper 183, 66 p.

Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., 1927, Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., v. 11, p. 785–808.

Bateman, A. M., 1951, The formation of mineral deposits: New York, John Wiley & Sons, Inc., 371 p.

Brown, H. S., Blake, W. J., Chodas, A. A. Kowalkowski, Richard, McKinney, C. R., Neuerburg, G. J., Silver, L. T., and Uchiyama, Aiji, 1953, Leaching studies of interstitial materials in igneous rocks [abs.]: Geol. Soc. America Bull., v. 64, p. 1400–1401.

Brown, R. W., 1950, Cretaceous plants from southwestern Colorado; U.S. Geol. Survey Prof. Paper 221–D, p. 45–66.

Burwell, Blair, 1920, Carnotite mining in southwestern Colorado: Eng. Mining Jour., v. 110, no. 16, p. 755–758.

Butler, B. S., Loughlin, G. F., Heikes, V. C., and others, 1920, Ore deposits of Utah: U.S. Geol. Survey Prof. Paper 111, 672 p.

Byerly, P. E., and Joesting, H. R., 1959, Regional geophysical investigation of the Lisbon Valley area Utah and Colorado: U.S. Geol. Survey Prof. Paper 316–C, p. 50.

Carter, W. D., 1957, Disconformity between Lower and Upper Cretaceous in western Colorado and eastern Utah: Geol. Soc. America Bull., v. 68, no. 3, p. 307–314.

Carter, W. D., and Gualtieri, J. L., 1965, Geyser Creek Fanglomerate (Tertiary), La Sal Mountains, eastern Utah: U.S. Geol. Survey Bull. 1224–E, 11 p.

Case, J. E., Joesting, H. R., and Byerly, P. E., 1963, Regional geophysical investigations in the La Sal Mountains area, Utah and Colorado: U.S. Geol. Survey Prof. Paper 316–F, p. 91–116.

Cater, F. W., Jr., 1954a, Geology of the Bull Canyon quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ–33.

——— 1954b, Geology of the Gateway quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ–55.

Cobban, W. A., and Reeside, J. B., Jr., 1952, Correlation of the Cretaceous formations of the western interior of the United States: Geol. Soc. America Bull., v. 63, p. 1011–1043.

Coffin, R. C., 1921, Radium, uranium, and vanadium deposits of southwestern Colorado: Colorado Geol. Survey Bull. 16, 231 p.

——— 1954, History of radium-uranium mining in the Plateau Province, *in* Uranium deposits and general geology of southeastern Utah: Utah Geol. Soc. Guidebook to the Geology of Utah, no. 9, p. 1–7.

Craig, L. C., and Dickey, D. D., 1956, Jurassic strata of southeastern Utah and southwestern Colorado, *in* Geology and economic deposits of east central Utah, 1956: Intermountain Assoc. Petroleum Geologist Guidebook 7th Ann. Field Conf., p. 93–104.

Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L., and others, 1955, Stratigraphy of the Morrison and related formation, Colorado Plateau region, a preliminary report: U.S. Geol. Survey Bull. 1009–E, p. 125–168.

Cross, Whitman, 1894a, Pikes Peak Colorado: U.S. Geol. Survey Geol. Atlas, Folio 7.

——— 1894b, The laccolithic mountain groups of Colorado, Utah and Arizona: 14th Ann. Rept. U.S. Geol. Survey, pt. 2, p. 230.

Cross, Whitman, and Purington, C. W., 1899, Description of the Telluride quadrangle [Colorado]: U.S. Geol. Survey Geol. Atlas, Folio 57.

Cross, Whitman, Spencer, A. C., and Purington, C. W., 1899, Description of the La Plata quadrangle [Colorado]: U.S. Geol. Survey Geol. Atlas, Folio 60.

Dane, C. H., 1935, Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U.S. Geol. Survey Bull. 863, 184 p.

Davis, G. L., 1954, Age of rocks, *in* Annual report of the Director of the Geophysical Laboratory: Carnegie Inst. Washington, Yearbook 53, p. 104–106.

Dutton, C. E., 1880, Geology of the high plateaus of Utah: U.S. Geol. Geog. Survey, Rocky Mountain region (Powell), v. 32, 304 p.

Dutton, C. E., 1882, The Tertiary history of the Grand Canyon district: U.S. Geol. Survey Mon. 2, 264 p.

——— 1885, Mountain Taylor and Zuni Plateau: U.S. Geol. Survey 6th Ann. Rpt., p. 105–198.

Fenneman, Nevin M., 1931, Physiography of western United States: New York, McGraw-Hill Book Co.

Fischer, R. P., 1936, Peculiar hydrothermal copper-bearing veins of the northwestern Colorado Plateau: Econ. Geology, v. 31, no. 6, p. 571–599.

——— 1937, Sedimentary deposits of copper, vanadium, uranium, and silver in southwestern United States: Econ. Geology, v. 32, p. 906–951.

——— 1942, Vanadium deposits of Colorado and Utah: U.S. Geol. Survey Bull. 936–P, p. 363–394.

Fischer, R. P., and Hilpert, L. S., 1952, Geology of the Uravan mineral belt: U.S. Geol. Survey Bull. 988–A, p. 1–13.

Forrester, J. D., 1946, Principles of field and mining geology: New York, John Wiley & Sons, Inc.

Garrels, R. M., and Christ, C. L., 1959, Behavior of Colorado Plateau uranium minerals during oxidation, *in* Garrels, R. M., and Larsen, E. S., 3d, Compilers, Geochemistry and mineralogy of Colorado Plateau uranium ores: U.S. Geol. Survey Prof. Paper 320, p. 81–89.

Gilbert, G. K., 1877, Report on the geology of the Henry Mountains: U.S. Geol. Geog. Survey, Rocky Mountain region (Powell), 160 p.

Gilluly, James, and Reeside, J. B., Jr., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U.S. Geol. Survey Prof. Paper 150–D, p. 61–110.

Goddard, E. N., chm., and others, 1948, Rock color chart: Washington, Natl. Research Council (repub. by Geol. Soc. America, 1951), 6 p.

Gould, L. M., 1926, The geology of the La Sal Mountains of Utah: Michigan Acad. Sci. Arts and Letters, v. 7, p. 55–106.

Gregory, H. E., 1917, Geology of the Navajo country—a reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geol. Survey Prof. Paper 93, 161 p.

——— 1938, The San Juan country, a geographic and geologic reconnaissance of southeastern Utah: U.S. Geol. Survey Prof. Paper 188, 123 p.

Gregory, H. E., and Moore, R. C., 1931, Geology of the Kaiparowits region, Utah and Arizona: U.S. Geol. Survey Prof. Paper 164, p. 61.

Gruner, J. W., 1956, Concentration of uranium in sediments by multiple migration-accretion: Econ. Geology, v. 51, p. 495–520.

Haff, J. C., 1944, Petrology of two clastic dikes from the Placerville district, Colorado: Am. Jour. Sci., v. 242, no. 4, p. 204–217.

Harshbarger, J. W., Repenning, C. A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and Jurassic rocks of the Navajo country: U.S. Geol. Survey Prof. Paper 291, 74 p.

Hill, James J., 1913, Notes on the Northern La Sal Mountains, Grand County, Utah: U.S. Geol. Survey Bull. 530, p. 99–118.

Hodgman, C. D., Weast, R. C., Wallace, C. W., and Selby, S. M., 1955, Handbook of chemistry and physics: Cleveland, Ohio, Chemical Rubber Pub. Co., 3173 p.

Hunt, C. B., 1942, New interpretation of some laccolithic mountains and its possible bearing on structural traps for oil and gas: Am. Assoc. Petroleum Geologist Bull., v. 26, p. 197–203.

Hunt, C. B., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geol. Survey Prof. Paper 228, 234 p.

——— 1954, Structural and igneous geology of the La Sal Mountains, Utah: Science, v. 119, no. 3093, p. 477–478.

——— 1956, Cenozoic geology of the Colorado Plateau: U.S. Geol. Survey Prof. Paper 279, 99 p.

——— 1958, Structural and igneous geology of the La Sal Mountains, Utah, *with a section on* Origin of magmas, by A. C. Waters: U.S. Geol. Survey Prof. Paper 294–I, p. 305–364.

Hurley, P. M., 1950, Distribution of radioactivity in granites and possible relation to helium age measurement: Geol. Soc. America Bull., v. 61, p. 1–8.

Iddings, J. P., 1898, Bysmaliths: Jour. Geology, v. 6, p. 704–710.

Jobin, D. A., 1956, Regional transmissivity of the exposed sediments of the Colorado Plateau as related to distribution of uranium deposits, *in* Page and others: U.S. Geol. Survey Prof. Paper 300, p. 207–212.

Katich, P. J., Jr., 1951, Recent evidence for Lower Cretaceous deposits in Colorado Plateau: Am. Assoc. Petroleum Geologist Bull., v. 35, p. 2093–2094.

Kiersch, G. A., 1950, Small scale structures and other features of Navajo Sandstone, northern part of San Rafael Swell, Utah: Am. Assoc. Petroleum Geologists Bull., v. 34, p. 923–942.

Kimball, Gordon, 1904, Discovery of Carnotite: Eng. Mining Jour., v. 77, p. 956.

Kimball, S. H., 1929, The Fountain and Casper Formations of the Laramie Basin, a study on genesis of sediments: Wyoming Univ. Pub. Sci. Geology, v. 1, 82 p.

Knight, S. H., 1930, Festoon cross-lamination [abs.]: Geol. Soc. America Bull., v. 41, p. 86: Pan–Am. Geologist, v. 53 p. 130.

Lewis, G. Edward, Irwin, J. H., and Wilson, R. F., 1961, Age of the Glen Canyon Group (Triassic and Jurassic) on the Colorado Plateau: Geol. Soc. America Bull., v. 72, no. 9, p. 1437–1440.

Lowell, J. D., 1955, Application of cross stratification studies to problems of uranium exploration, Chuska Mountains, Arizona: Econ. Geology, v. 50, no. 2, p. 177–185.

Lupton, C. T., 1914, Oil and gas near Green River, Grand County, Utah: U.S. Geol. Survey Bull. 541–D, p. 115–133.

McKay, E. J., 1955, Criteria for outlining areas favorable for uranium deposits in parts of Colorado and Utah: U.S. Geol. Survey Bull. 1009–J, p. 265–282.

McKelvey, V. E., Everhart, D. L., and Garrels, R. M., 1955, Origin of uranium deposits: Econ. Geology, 50th Anniversary volume, p. 464–533.

——— 1956, Summary of hypotheses of genesis of uranium deposits, *in* Page, Stocking, and Smith: U.S. Geol. Survey Prof. Paper 300, p. 41–53.

Page, L. R., Stocking, H. E., and Smith, H. B., compilers, 1956,

Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955: U.S. Geological Survey Prof. Paper 300, 739 p.

Peale, A. C., 1877a, On a peculiar type of eruptive mountains in Colorado: U.S. Geol. Geog. Survey Terr., Bull., v. 3, p. 551–564.

——— 1877b, On the Grand River district: U.S. Geol. Geog. Survey Terr., 9th Ann. Rept., 1875, p. 59–62, 80–92, 95–98.

Pettijohn, F. J., 1949, Sedimentary rocks: New York, Harper Bros., 526 p.

Poole, F. G., and Williams, G. A., 1956, Direction of sediment transport in rocks of the Colorado Plateau as determined from primary sedimentary structures *in* Page and others: U.S. Geol. Survey Prof. Paper 300, p. 227–232.

Powell, J. W., 1875, Exploration of the Colorado River of the west and its tributaries: Washington, D.C., Smithsonian Inst., 291 p.

———1876, Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto: U.S. Geol. Geog. Survey Terr. (Powell), v. 7, 218 p.

Rasor, C. A., 1952, Uraninite from the Gray Daun mine, San Juan County, Utah: Science, v. 116, no. 3004, p. 89–90.

Raup, O. B., and Miesch, A. T., 1957, A new method for obtaining significant average directional measurements in cross-stratification studies: Jour. Sed. Petrology, v. 27, no. 3, p. 313—321.

Reeside, J. B., Jr., 1924, Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin, Colorado and New Mexico: U.S. Geol. Survey Prof. Paper 134, p. 1–55.

Reinhardt, E. V., 1952, The distribution of uranium and vanadium deposits in the Colorado Plateau relative to Tertiary instrusive masses: U.S. Atomic Energy Comm. RMO 816, issued by U.S. Atomic Energy Comm.: Tech. Inf. Service, Oak Ridge, Tenn.

Richmond, G. E., 1962, Quaternary stratigraphy of the La Sal Mountains, Utah: U.S. Geol. Survey Prof. Paper 324, 135 p.

Roach, C. H., and Thompson, M. E., 1959, Sedimentary structures and the localization and oxidation of ore at the Peanut mine, Montrose County, Colorado, *in* Garrels, R. M., and Larsen, E. S., 3d, compilers, Geochemistry and mineralogy of Colorado Plateau uranium ores: U.S. Geol. Survey Prof. Paper 320, p. 197–202.

Shawe, D, R., 1956, Significance of roll ore bodies in genesis of uranium-vanadium deposits on the Colorado Plateau, *in* Page and others: U.S. Geol. Survey Prof. Paper 300, p. 239–241.

Shoemaker, E. M., 1951, Internal structure of the Sinbad Valley-Fisher Valley salt anticline, Colorado and Utah [abs.]: Geol. Soc. America Bull., v. 63, p. 1478.

——— 1954, Structural features of southeastern Utah and adjacent parts of Colorado, New Mexico, and Arizona: Utah Geol. Soc. Guidebook to Geology of Utah, no. 9, p. 48–69.

——— 1955, Structural features of the Colorado Plateau and their relation to uranium deposits, *in* Page and others: U.S. Geol. Survey Prof. Paper 300, p. 155–170.

——— 1956a, Geology of the Roc Creek quadrangle, Colorado: U.S. Geol. Survey Quad. Map GQ–83.

——— 1956b, Precambrian rocks of the north-central Colorado Plateau, *in* Geology and economic deposits of east central Utah: Intermountain Assoc. Petroleum Geologists Guidebook 7th Ann. Field Conf., p. 54–57.

Shoemaker, E. M., and Newman, W. L., 1959, Moenkopi Formation (Triassic? and Triassic) in salt anticline region, Colorado and Utah: Am. Assoc. Petroleum Geologists, Bull., v. 43, no. 8, p. 1835–1851.

Simmons, G. C., 1957, Contact of Burro Canyon Formation with Dakota Sandstone, Slick Rock district, Colorado, and correlation of Burro Canyon Formation: Am. Assoc. Petroleum Geologist Bull., v. 41, no. 11, p. 2519–2529.

Stewart, J. H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 3, p. 441–465.

Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., 1959, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, *with a section on* sedimentary petrology by R. A. Cadigan: U.S. Geol. Survey Bull. 1046–Q, p. 487–576.

Stieff, L. R., Stern, T. W., and Sherwood, A. M., 1955, Preliminary description of coffinite—a new uranium mineral (Colorado Plateau): Sci. v. 121, no. 3174, p. 608–609.

Stokes, W. L., 1944, Morrison Formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., v. 55, p. 951–992.

——— 1952, Lower Cretaceous in Colorado Plateau: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 1766–1776.

Stokes, W. L., and Holmes, C. N., 1954, Jurassic rocks of south central Utah, *in* Intermountain Assoc. Petroleum Geologist Guidebook 5th Ann. Field Conf., Geology of portions of the High Plateaus and adjacent Canyon lands, central and south-central, Utah: p. 34–41.

Stokes, W. L., and Phoenix, D. A., 1948, Geology of the Egnar-Gypsum Valley area, San Miguel and Montrose Counties, Colorado: U.S. Geol. Survey Prelim. Oil and Gas Inv. Map 93.

Trites, A. F., and Chew, R. T., III, 1955, Geology of the Happy Jack Mine, White Canyon area, San Juan County, Utah: U.S. Geol. Survey Bull. 1009–H, p. 235–248.

Ward, L. F., 1901, Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., v. 12, p. 401–413.

Waters, A. C., 1955, Volcanic rocks and the tectonic cycle, *in* Poldervaart, Arie, ed., Crust of the earth—a symposium: Geol. Soc. America Spec. Paper 62, p. 703–722.

Weeks, A. D., and Thompson, M. E., 1954, Identification and occurrence of uranium and vanadium minerals from the Colorado Plateaus: U.S. Geol. Survey Bull. 1009–B, p. 13–62.

Weir, D. B., 1952, Geologic guides to prospecting for carnotite deposits on Colorado Plateau: U.S. Geol. Survey Bull. 988–B, p. 15–27.

Withington, C. F., 1956, Geology of the Paradox quadrangle, Colorado: U.S. Geol. Survey Quad. Map GQ–72.

Witkind, I. J., and Thaden, R. E., 1963, Geology and uranium-vanadium deposits of the Monument Valley area, Apache and Navajo Counties, Arizona, *with sections on* Serpentine at Garnet Ridge, by H. E. Malde and R. E. Thaden, *and* Mineralogy and paragenesis of the ore deposit at the Monument No. 2 and Cato Sells mines, by D. H. Johnson: U.S. Geol. Survey Bull. 1103, 171 p.

Wright, J. C., Shawe, D. R., and Lohman, S. W., 1962, Definition of members of Jurassic Entrada Sandstone in east-central Utah and west-central Colorado: Am. Assoc. Petroleum Geologists Bull., v. 46, no. 11, p. 2057–2070.

# INDEX

[Italic page numbers indicate major references]

U.S. GOVERNMENT PRINTING OFFICE: 1965 O—777-039