Structure of the Slick Rock District and Vicinity, San Miguel and Dolores Counties, Colorado

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GEOLOGIC INVESTIGATIONS IN THE SLICK ROCK DISTRICT, SAN MIGUEL AND DOLORES COUNTIES, COLORADO

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By Daniel R. Shawe

ABSTRACT

Major folds in the district are the northwesterly oriented Dolores anticline and Disappointment syncline, adjacent to the parallel Gypsum Valley anticline bordering the northeast edge of the district. A zone of faults bounds the southwest edge of the collapsed crest of Gypsum Valley anticline. The Dolores zone of faults extends southeastward into the district from Utah, obliquely across the Dolores anticlinal axis. Faults normal to the Dolores zone of faults in the northwestern part of the district constitute a conjugate set. The Glade zone of faults, trending about N. 75° E., extends through the southern part of the district. A major set of fractures nearly parallels the principal individual faults in the district, about N. 60°–70° W.; a less prominent set nearly parallels the faults normal to the Dolores zone, about N. 45° E.

Major zones of faults and folds in the district were deformed, at times simultaneously, during deposition of the upper Paleozoic and Mesozoic rocks, as shown by thickness variation of the formations related to zones of faults and the fold axes. The zones of faults appear to be parts of a major regional conjugate system, and deformation on these zones was probably related to folding of the salt anticlines (including Gypsum Valley and Dolores anticlines) and development of the Paradox Basin.

Most faults and joints visible in the Gypsum Valley, Dolores, and Glade zones of faults are younger than strata of Late Cretaceous age, and they controlled movement of solutions that epigenetically altered the rock, probably in early to middle Tertiary time. Such epigenetic alteration was probably related to deposition of the uranium-vanadium ores of the district. Fracturing that followed the episode of alteration displaced mineralized rocks and was in part related to late Tertiary collapse of the Gypsum Valley salt anticline or to late growth of the Dolores anticline during the Quaternary.

INTRODUCTION

The Slick Rock district lies in the Paradox Basin at the south edge of the salt anticline region, also called the Paradox fold and fault belt (Kelley, 1958) (fig. 1). The district, which covers about 570 square miles, is underlain by about 13,000 feet of sedimentary strata lying upon metamorphic and igneous rocks of a Pre-
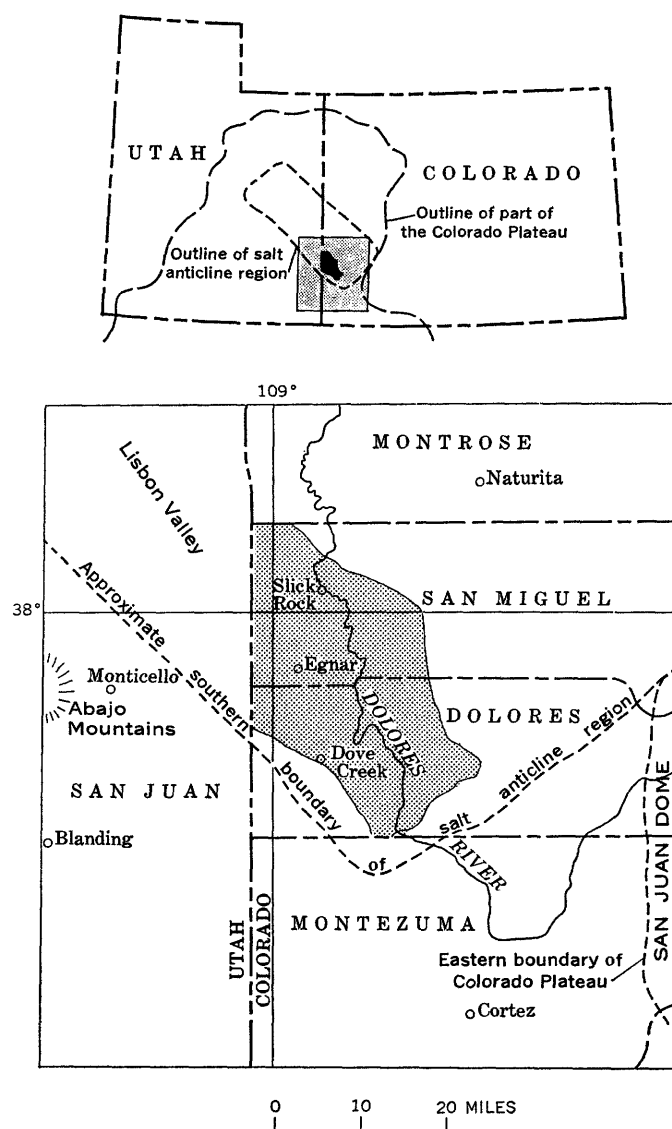

FIGURE 1.—Location of the Slick Rock district (stippled area).

cambrian basement. The sedimentary formations range in age from Cambrian to Late Cretaceous, and are summarized in table 1. They have already been described in detail in the first two reports of this series (Shawe and others, 1968; Shawe, 1968). Data already published on thickness variations of the formations (Shawe and others, 1968) are here used as the basis for inferring certain structural relations.

Sedimentary rocks in the district have been extensively altered (bleached). Diagenetically bleached and altered zones generally coincide with zones of abundant carbonaceous plant material in some stratigraphic units (particularly the upper part of the Salt Wash Member of the Morrison Formation and the Moss Back Member of the Chinle Formation). Epigenetically bleached and altered zones generally coincide with structural elements such as faults, joints, and the axial regions of folds. Where zones of carbonaceous material and structures are closely associated, the altered rocks may contain uranium-vanadium deposits, indicating a significant structural control of mineralization. The Salt Wash Member, in the northern part of the district in the vicinity of a prominent zone of faults, has yielded a large amount of uranium-vanadium ore. This report is intended to describe the structure of the district in order to provide a background for understanding the localization and origin of altered rocks and contained ore deposits, subjects to be dealt with in later reports of this series.

Major folds in the district trend northwesterly and are nearly parallel to the collapsed Gypsum Valley salt anticline which lies at the northeast edge of the district (fig. 2). The Dolores anticline is about 10 miles southwest of the Gypsum Valley anticline and is separated from it by the Disappointment syncline.

A fold identified as the Glade anticline has been indicated by some authors as extending into the Slick Rock district. Finley (1951) labeled a sinuous fold south of the district as the Glade anticline, but structure contours controlled by topography (Shawe and others, 1968, pl. 1) do not substantiate such a fold. Instead, only a part of the anticline mapped by Finley is indicated, and this coincides with the position of the Dove Creek anticline. Kelley (1955, figs. 2, 8) showed the Dolores anticline extending both southeastward and east-southeastward from the vicinity of the Glade graben. The author and colleagues (Shawe and others, 1959, figs. 2, 5), in an earlier report on the Slick Rock district, designated a fold that extends southeastward from the center of the district as the Dolores anticline, and one that extends east-southeastward, as the Glade anticline. Because of the lack of evidence in the struc-

ture contour map for another fold besides the Dolores anticline, and the confusion concerning the position of the Glade anticline, the name should no longer be used to designate an anticline in this region.

A zone of faults bounds the southwest edge of the core of the Gypsum Valley anticline and thereby forms the northeast boundary of the district. The Dolores zone of faults lies farther southwest, parallel to, and about 2 miles northeast of, the axis of the Dolores anticline. A few faults normal to the Dolores zone of faults in the northwestern part of the district constitute a conjugate set. The Glade zone of faults, which trends about N. 75° E., extends through the southern part of the district. The axis of the Dolores anticline is offset along the Glade zone of faults.

A major set of joints is oriented parallel to the principal faults in the district; a less prominent set approximately parallels the faults normal to the Dolores zone.

STRUCTURE IN THE PRECAMBRIAN BASEMENT

Geophysical data gathered by H. R. Joesting and coworkers (oral commun., 1956–57), and deep oil-test well information (Shawe and others, 1968, pl. 3), suggest that the general elevation of the basement underlying the Slick Rock district is about 4,000 feet below sea level. A major regional structural element in the basement rocks, probably a fault or fault zone with considerable dip-slip displacement, possibly several thousand feet, down on the northeast side, lies beneath, and parallel to, the northwesterly axis of the Disappointment syncline (Joesting and Case, 1960, fig. 114.2). The interpreted fault thus forms the southwest edge of a very large graben about 30 miles wide, the northeast edge of which is the fault zone bordering the Uncompahgre Plateau. On a map showing the configuration of the surface of Precambrian basement rocks based on deep drill-hole information (fig. 3), an abrupt northeasterly declivity indicates the approximate position of the interpreted fault bounding the large graben.

A narrow troughlike depression in the basement, oriented about normal to the large graben and passing under the south end of the district, probably reflects large basement faults or a fault zone (fig. 3). This zone appears to be a northeasterly continuation of a structural zone beneath the Blanding basin, Utah, west of Slick Rock, as interpreted from geophysical data by Case and Joesting (1961, p. D287–D291 and figs. 393.1, 393.2). A basement fault zone inferred to bound the northwest side of the basement trough is discussed frequently in subsequent pages and, for convenience, is here termed the "Glade subsurface fault zone" (fig. 3).

TABLE 1.—*Summary of consolidated sedimentary rocks in the Slick Rock district*

Age	Formation and member	Thickness (feet)	Description
Late Cretaceous	Mancos Shale	1, 600–2, 300	Dark-gray carbonaceous, calcareous shale.
	Dakota Sandstone	120–180	Light-buff sandstone and conglomeratic sandstone, dark-gray carbonaceous shale, and coal.
Early Cretaceous	Burro Canyon Formation	40–400	Light-gray to light-buff sandstone and conglomeratic sandstone; greenish-gray and gray shale, siltstone, limestone, and chert.
Late Jurassic	Morrison Formation, Brushy Basin Member	300–700	Reddish-brown and greenish-gray mudstone, siltstone, sandstone, and conglomerate.
	Morrison Formation, Salt Wash Member	275–400	Light-reddish-brown, light-buff, and light-gray sandstone and reddish-brown mudstone.
	Junction Creek Sandstone	20–150	Light-buff sandstone.
	Summerville Formation	80–160	Reddish-brown siltstone and sandstone.
	Entrada Sandstone, Slick Rock Member	70–120	Light-buff to light-reddish-brown sandstone.
	Entrada Sandstone, Dewey Bridge Member	20–35	Reddish-brown silty sandstone.
Jurassic and Triassic(?)	Navajo Sandstone	0–420	Light-buff and light-reddish-brown sandstone.
Late Triassic(?)	Kayenta Formation	160–200	Purplish-gray to purplish-red siltstone, sandstone, shale, mudstone, and congolmerate.
Late Triassic	Wingate Sandstone	200–400	Light-buff and light-reddish-brown sandstone.
	Chinle Formation, Church Rock Member	340–500	Reddish-brown, purplish-brown, and orangish-brown sandstone, siltstone, and mudstone; dark-greenish-gray conglomerate.
	Chinle Formation, Petrified Forest(?) Member	0–100	Greenish-gray mudstone, siltstone, shale, sandstone, and conglomerate.
	Chinle Formation, Moss Back Member.	20–75	Light-greenish-gray and gray sandstone and conglomerate; minor greenish-gray and reddish-brown mudstone, siltstone, and shale.
Middle(?) and Early Triassic	Moenkopi Formation	0–200	Light-reddish-brown siltstone and sandy siltstone.
Early Permian	Cutler Formation	1, 500–3, 000	Reddish-brown, orangish-brown, and light-buff sandstone, siltstone, mudstone, and shale.
Late and Middle Pennsylvanian	Rico Formation	130–240	Transitional between Cutler and Hermosa Formations.
Middle Pennsylvanian	Hermosa Formation, upper limestone member	1, 000–1, 800	Light- to dark-gray limestone; gray, greenish-gray, and reddish-gray shale and sandstone.
	Hermosa Formation, Paradox Member	3, 250–4, 850	Upper and lower units gray dolomite, limestone, and dark-gray shale interbedded with evaporites; middle unit halite and minor gypsum, anyhdrite, dolomite, limestone, and black shale.
	Hermosa Formation, lower limestone member	100–150	Medium-gray limestone, dark-gray shale.
Early Pennsylvanian and Mississippian	Molas Formation	100	Reddish-brown, dark-gray, and greenish-gray shale and silty shale and gray limestone.
Mississippian	Leadville Limestone	240	Medium-gray limestone and dolomite.
Devonian	Name not assigned	250–550	Gray sandy dolomite and limestone and grayish-green and reddish sandy shale.
Cambrian	Name not assigned	500–700	Light-gray to pinkish conglomeratic sandstone, sandstone, siltstone, shale, and dolomite.
Precambrian	Name not assigned	--------------	Granitic to amphibolitic gneisses and schists, and granite.

FIGURE 2.—Structural map of the Slick Rock district (light stipple) and vicinity showing major folds and fault zones. Structure contours are on the base of the Dakota Sandstone; contour interval 250 feet, dashed where projected above the surface. Data modified from P. L. Williams (1964; written commun., 1965). Heavy lines indicate inferred deep-seated shear faults; arrows show direction of inferred lateral slip.

FIGURE 3.—Summary of major thinning and thickening trends in some Paleozoic and Mesozoic sedimentary formations in and near the Slick Rock district (fine stipple) and their relation to inferred upper surface of Precambrian rocks (shown by structure contours) and Glade subsurface fault zone. Dots indicate oil-test wells used for control of structure contours. From Shawe, Simmons, and Archbold (1968, fig. 2).

MAJOR FOLDS

The dominant structure in the Slick Rock district is the Dolores anticline (fig. 4). Its size and dominance is strikingly revealed by the canyon of the Dolores River, which is 2,000 feet deep where it cuts diagonally across the anticline and which exposes rocks as old as Permian in the core of the structure. The anticline is a broad, gently arched fold that extends southeasterly through the district for a distance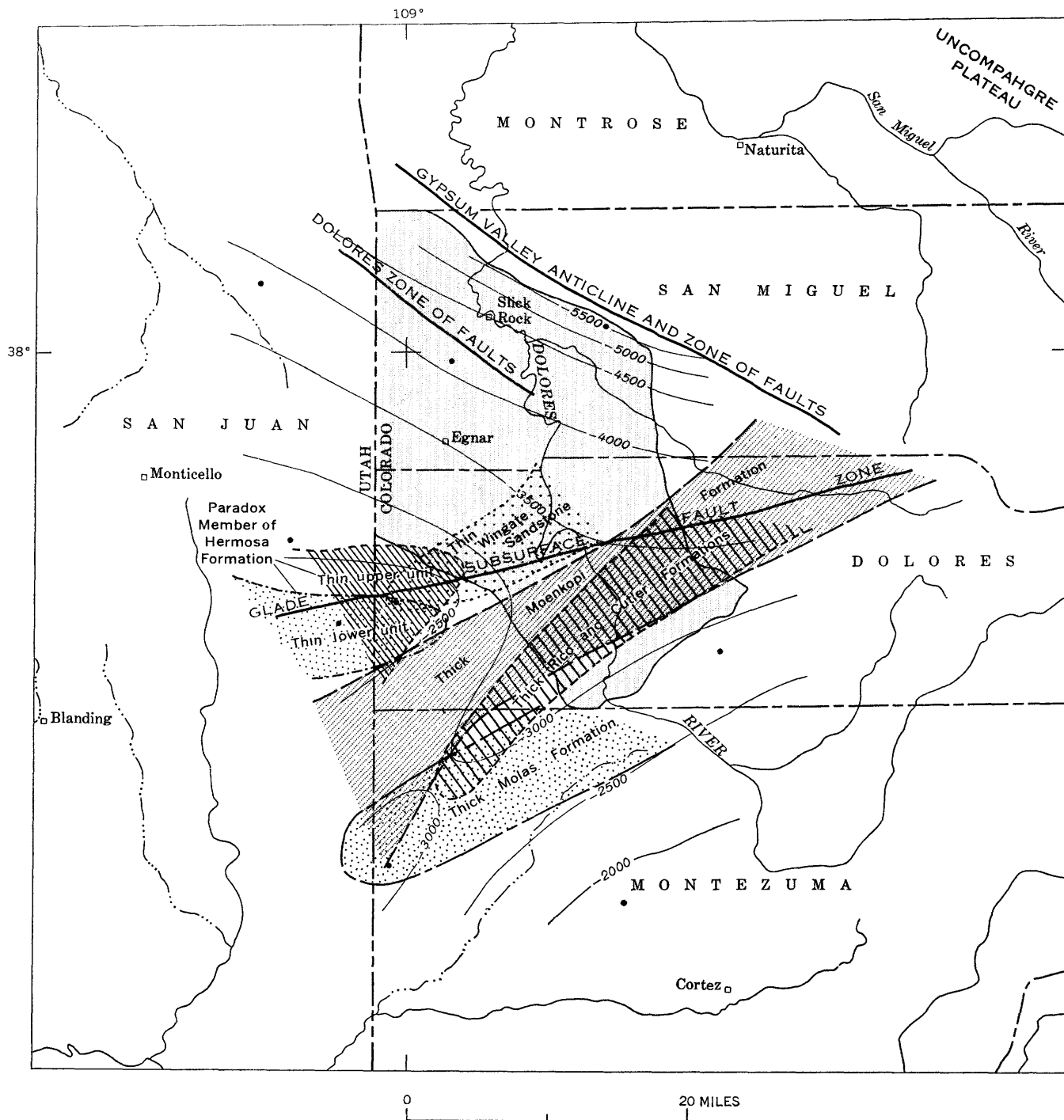 of about 35 miles. The breadth of the anticline is more than 10 miles. It plunges both northwestward and southeastward from the vicinity of the Glade graben, and closure on the structure probably exceeds 500 feet (fig. 2). The axis of the anticline is poorly defined in the Dolores zone of faults at the west edge of the district, but the plunge continues northwesterly outside the district. Farther to the northwest the anticline rises to form another elongate dome, the Lisbon Valley anticline. To the southeast and outside the district, the Dolores anticline appears to merge with the broad domal uplift of the western San Juan Mountains.

The Dolores anticline is asymmetric; the southwest limb has a maximum dip of 2° in the area between Egnar and the Dolores River, whereas the northeast limb dips as much as 9° in the vicinity of Joe Davis Hill (Shawe and others, 1968, pl. 1). The axis of the Dolores anticline is somewhat sinuous, and trends about N. 45° W. in the north half of the Slick Rock district and about N. 45°–70° W. in the south half.

An exceptionally thick section of salt, anhydrite, dolomite, and black shale in the Paradox Member of the Hermosa Formation of Pennsylvanian age underlies the Dolores anticline. Normal thickness of the Paradox Member southwest of the anticline under the Sage Plain is about 2,000 feet (Finley, 1951), whereas the thickness under the axis of the anticline within the district exceeds 4,000 feet (Shawe and others, 1968, fig. 6). The anticline formed partly because evaporite beds of the Paradox intruded upward in a manner similar to the other salt anticlines of the Paradox Basin (such as nearby Gypsum Valley anticline). Unlike most of the other salt anticlines, no Paradox beds are exposed in the Dolores anticline, nor has the crest of the anticline collapsed as the result of extrusion and solution of evaporites as in most of the other salt anticlines (Prommel and Crum, 1927; Stokes and Phoenix, 1948).

The Disappointment syncline, a broad fold, but tighter than the Dolores anticline, extends almost 25 miles parallel to the anticline within the district. The syncline is about 5 miles wide and forms a closed structural basin beneath Disappointment Valley. It plunges steeply from the northwest into the basin, and less steeply from the southeast. Northwestward, outside the district, a structural saddle separates the Disappointment syncline from the Coyote Wash syncline in Utah; to the southeast the syncline flattens, is complicated by faults and other folds, and merges with the broad structural dome of the western San Juan Mountains.

Like the Dolores anticline, the Disappointment syncline is asymmetric; the southwest limb dips 9° in the vicinity of Joe Davis Hill, whereas the northeast limb dips into the valley more steeply, as much as 32° northwest of Gypsum Gap (Shawe and others, 1968, pl. 1). The average trend of the axis of the Disappointment syncline in the Slick Rock district is about N. 55° W., but the syncline has sinuosities through its length nearly paralleling the zone of faults bounding Gypsum Valley. The axes of the syncline and the Dolores anticline di-
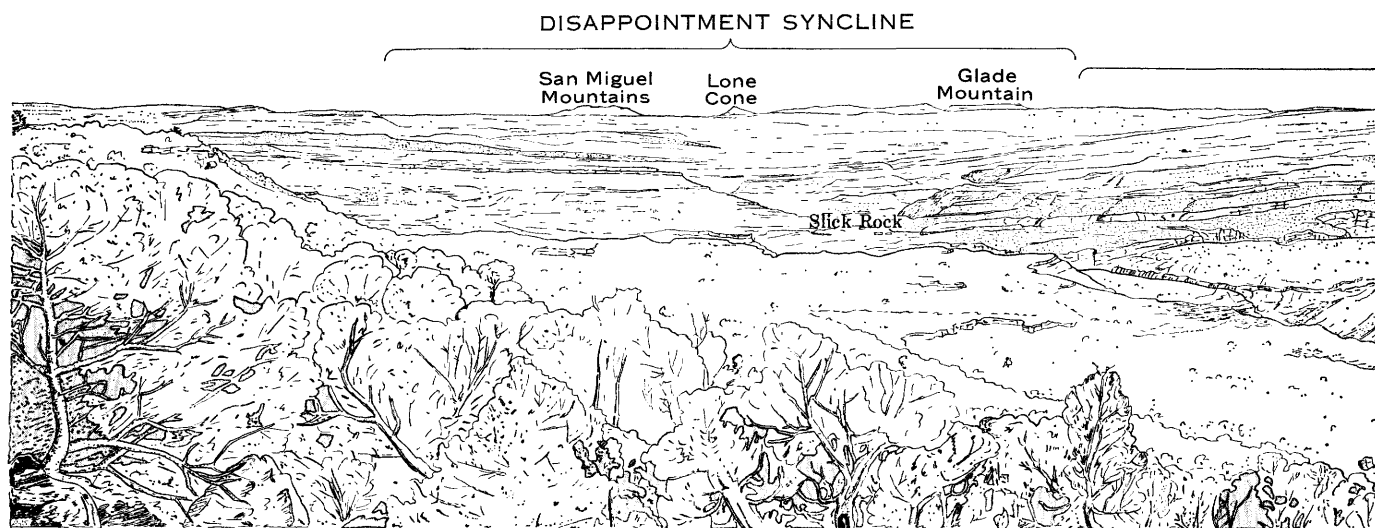

FIGURE 4.—Panoramic view of the Slick Rock

verge from about 5 miles apart in the northwest corner of the district to about 10 miles apart near the east edge of the district.

Most of the formations underlying the Disappointment syncline are thicker than in surrounding areas. For example, the aggregate thickness of strata from the base of the Kayenta Formation to the top of the Dakota Sandstone is about 2,500 feet under the syncline, whereas the aggregate thickness of the interval is only about 1,250 feet under the adjacent Dolores anticline.

The deepest part of the Disappointment synclinal basin, if the top of the Dakota Sandstone is used as a structure datum, lies near the east edge of the district. The highest part of the Dolores anticlinal dome lies almost due south, in the vicinity of the Glade graben. Maximum structural relief on the Dakota Sandstone between these two folds appears to be more than 3,000 feet. At the horizon of the Kayenta Formation the structural relief is probably more than 4,000 feet.

AGE OF THE MAJOR FOLDS

Isopach maps of stratal units as old as the Molas Formation (Baars, 1965) give indications that folding or faulting occurred during the Devonian Period parallel to the present major folds in the district. Not until deposition of the Rico and Cutler Formations of Pennsylvanian and Permian age (Shawe and others, 1968, fig. 10), however, did the position of the Disappointment syncline become clearly established as it is today. Permian rocks thicken in the Disappointment syncline to more than 3,000 feet (3,177 ft of Cutler Formation in Shell Oil Co. Gypsum Valley 2, sec. 16, T. 44 N., R. 18 W.; American Stratigraphic Co.). In post-Permian time, very little folding of the Dolores anticline and Disappointment syncline took place until, or

shortly after, the Navajo Sandstone was deposited, in Jurassic time.

The consistent thickening of almost all the sedimentary formations in the interval from Lower Jurassic to Upper Cretaceous in the basin of the Disappointment syncline indicates that post-Triassic folding was gradual. However, because the Navajo Sandstone, Brushy Basin Member of the Morrison Formation, and Burro Canyon Formation show relatively greater thickening compared to other formations, it is clear that the folding was accelerated during certain times in this long interval—namely, early in the Jurassic and again at the close of Jurassic and start of Cretaceous time.

Near the end of Cretaceous time, following deposition of the Mancos Shale, at least 1,500 feet of structural relief had developed between the Dolores anticline and the Disappointment syncline at the top of the Salt Wash Member of the Morrison Formation, and probably at least 2,000 feet at the top of the Moss Back Member of the Chinle Formation. These figures will be useful in later discussions of the origin of ore deposits in the Salt Wash and Moss Back Members which took place probably in early to middle Tertiary time.

No direct evidence remains of early Tertiary folding of the Dolores anticline and Disappointment syncline. Appreciable folding possibly took place again just before or during the general uplift of the Colorado Plateau in middle Tertiary time.

Considerable arching of the Dolores anticline has occurred since the early Pleistocene. This arching is suggested by the fact that the present grade of the youngest terrace gravels in Disappointment Valley parallel to the anticline is about 40 feet per mile (Shawe and others, 1968, fig. 47), which is an average grade for untilted youngest deposits, and the grade of gravels

DOLORES ANTICLINE

district southwestward from Horse Range Mesa.

between the Dolores River and Glade Mountain normal to the anticline is about 150 feet per mile (their fig. 48), which is a typical grade for tilted lower Pleistocene gravels on the limb of the fold. The amount of uplift near the axis of the Dolores anticline at Glade Mountain was indicated by Shawe, Simmons, and Archbold (1968, fig. 48) to be about 1,000 feet. However, F. W. Cater (written commun., 1968) described the highest (oldest) terrace gravels on the southwest flank of Disappointment Valley as untilted; this fact raises some doubt that in this place much late Pleistocene folding occurred. Appreciable folding probably took place in early Pleistocene, or even in the latest Tertiary, and minor uplift of the anticline could have occurred during the Holocene. Structural relief on the Dakota Sandstone from synclinal to anticlinal axes at the end of the Cretaceous Period was nearly 1,000 feet; it is now about 3,000 feet after possibly 1,000 feet of Pleistocene folding, which suggests that the period of plateau uplift during the middle Tertiary must have involved about 1,000 feet of folding.

MINOR FOLDS

Several small folds, generally no more than 1 or 2 miles in length, lie along the northeast edge of the Slick Rock district (Shawe and others, 1968, pl. 1; Cater, 1955a–d). For about 12 miles between Gypsum Gap and Steamboat Hill, a series of small anticlines lies just below the rim of Gypsum Valley. These anticlines are relatively sharp folds immediately adjacent to the border faults at the southwest side of the Gypsum Valley collapsed anticline. They have the appearance of large drag folds against the border faults, but their structural development was probably more complex. Actual removal of evaporite beds by flowage from the underlying Paradox Member of the Hermosa Formation, which was partly responsible for the collapse of the Gypsum Valley anticline, also may have been responsible for the sharp sag of the beds abutting the collapsed anticline. The small folds thus may have developed as a result of initial rise of an evaporite core in the axis of the Gypsum Valley anticline and by subsequent sag as evaporites moved at depth axially into cupolas or were removed by solution.

In places along the rim of Gypsum Valley, tightly folded small synclines adjoin the small anticlines (Shawe and others, 1968, pl. 1: Cater, 1955a–d). Generally, these synclines are northeast of the anticlines and are outside the Slick Rock district. In a few places the northeast limb of a syncline passes into a second small anticline. The synclinal folds may have resulted from renewal of the rise of evaporites in the core of the Gypsum Valley anticline. The northeast limb of a small anticline at the edge of the Gypsum Valley graben may have been folded upward by renewed rise of the evaporite beds, and an adjacent synclinal trough may have developed. Locally, for example, just northeast of Cape Horn, a relatively tight small anticline has formed northeast of a small syncline (Shawe and others, 1968, pl. 1). A second collapse possibly took place here because of renewed transfer of underlying evaporites into cupolas along the main axis of the Gypsum Valley anticline.

AGE OF THE MINOR FOLDS

The minor folds are chiefly evident in beds of the Morrison Formation and hence are post-Morrison in age. By their form and position the minor folds appear to have developed during the main period of collapse of the Gypsum Valley anticline. The youngest rocks involved in the Gypsum Valley collapse are part of the Mesaverde Formation of latest Cretaceous age (Cater, 1955a), indicating that collapse occurred during the Cenozoic. Although no direct evidence points to the time during the Cenozoic that the major collapse occurred, Stokes and Phoenix (1948) and Cater (1955a–d) indicated that it occurred principally near the end of the Laramide orogeny, at the beginning of Tertiary time. More likely, the major collapse and development of the minor folds took place in the middle to late Tertiary, or possibly even Pleistocene, shortly after the last major uplift of the Dolores anticline.

MAJOR FAULTS

A zone of faults trending N. 45°–60° W., and bounding the southwest edge of the core of the Gypsum Valley anticline, lies along the northeast edge of the Slick Rock district. The Dolores zone of faults is 7 miles southwest of the Gypsum Valley border faults and about 2 miles northeast of, and parallel to, the axis of the Dolores anticline (N. 55° W.). Individual faults in the zone strike N. 60°–85° W. and form a series of small en echelon grabens. The zone extends northwestward to merge with the Lisbon Valley fault in Utah. The southern part of the district is cut by the Glade zone of faults, which trends about N. 80° E. and extends westward into the Verdure graben in Utah. Individual faults in the zone strike about N. 60°–70° W.; depression of a long narrow block between two of these faults has formed the Glade graben. The west-northwest trend of almost all the major faults within and bounding the Slick Rock district is notable.

FAULTS BOUNDING GYPSUM VALLEY

The zone of faults at the northeastern boundary of the district consists of several nearly parallel somewhat sinuous faults. Individual faults are no longer than about 4 miles, and they die out along the zone, giving way to nearly parallel faults slightly offset on strike (Cater, 1955a–d). Several small faults in the zone are not shown on the quadrangle maps by Cater (1955a–d), nor on the map of the Slick Rock district (Shawe and others, 1968, pl. 1). The faults, mapped and unmapped, are mostly high angle and appear to be normal, with the Gypsum Valley or northeast side down. None of the faults has had displacement of more than about 500 feet; where strata younger than those forming the rim of Gypsum Valley have collapsed into the core of the anticline as much as a few thousand feet, the displacement was accomplished by step faulting on sets of nearly parallel faults and by flexing. A few faults show a relative upward displacement on the valley side of the fault, which resulted in the formation of small horsts. These faults probably reflect local upward growth of the salt core of the anticline in cupolas, and thus they originated before the principal collapse of the structure.

In the vicinity of the Grassy Hills at the north end of the district (Shawe and others, 1968, pl. 1), intensive alteration has occurred along faults that show upward displacement of the Gypsum Valley side of the fault. In addition to bleaching of rocks, considerable iron staining has taken place near the faults. Similar alteration is associated with other faults in the zone along the southwest edge of the Gypsum Valley anticline. Some of the faults in the zone, however, do not appear to be bounded by altered rocks. This fact suggests two general periods of faulting—the first before a period of alteration and the second after it. By inference, then, uplift of the core of the anticline was accompanied by faulting along the margin, followed by passage of altering solutions along the marginal fault zone. Finally, collapse of the core of the anticline was accompanied by a second period of faulting, probably with renewed movements on many of the older faults, but also with the formation of new faults.

AGE OF THE GYPSUM VALLEY FAULTS

Some faults bounding the core of the Gypsum Valley anticline, not shown on the quadrangle maps and sections by Cater (1955a–d) but likely separating the Paradox Member of the Hermosa Formation of Pennsylvanian age from younger rocks, were formed before the deposition of Mesozoic rocks. The faults that are shown on Cater's maps must generally be of Cretaceous or younger age, for many of them, including those bounded by altered rocks, displace strata of Late Cretaceous age.

Time of this faulting may have been principally during the middle of the Tertiary Period and also during Pleistocene time. If principal growth of the salt anticlines was controlled fundamentally by regional compression, which seems likely and which is elaborated on later in this report, most of the faulting along the Gypsum Valley anticline probably coincided in time with periods of accelerated growth of the nearby Dolores anticline inferred as middle Tertiary and Pleistocene. In view of the flimsy basis for dating, however, the possibilities of faulting at other, perhaps numerous, intervals throughout the Cenozoic should be admitted.

DOLORES ZONE OF FAULTS

A zone of faults extending along the Dolores anticline in the northern part of the district was named the "Dolores fault zone" (Shawe and others, 1959, p. 397). Individual faults in the zone are separated in places as much as several hundred feet, however, so that "zone of faults" seems to be a more appropriate terminology than "fault zone." The faults are less than a mile to a few miles long, and chiefly bound small grabens disposed en echelon as if reflecting a northwesterly left-lateral shear. Displacement on the faults is generally slight. Only near the west boundary of the district is it appreciable, where one fault near the Empire group of mines has offset strata about 700 feet (Shawe and others, 1968, pl. 1). Farther northwest, in Utah, the Lisbon Valley fault, which is an extension of the Dolores zone of faults, has a maximum stratigraphic displacement of about 5,000 feet (Weir and Puffett, 1960, p. 134). Faults in the Dolores zone northwest of the town of Slick Rock are oriented about N. 70°–85° W., whereas those farther southeast trend about N. 55° W. and are more nearly parallel to the zone as a whole. A pronounced zone of east-striking joints, discussed in greater detail in the section on "Joints," separates the two groups of faults.

Faults on Slick Rock Hill about 3 miles southwest of the town of Slick Rock show successively less displacement upward in younger rocks and do not cut the youngest strata exposed (Shawe and others, 1968, pls. 1, 7). The lower part of the Morrison Formation thus locally "bridges" small grabens that displace the underlying Summerville Formation and Entrada Sandstone. Perhaps the faults merely flatten and die out upward so that deformation of higher strata consisted only of slight warping; or possibly faulting was taking place just before the Morrison deposition, but it had ceased by the end of Morrison deposition. The first explanation seems more logical, because some faults in the Dolores fault zone cut strata younger than the Morrison Formation.

AGE OF THE DOLORES ZONE OF FAULTS

Again, direct evidence of the age of the faulting in the Dolores zone of faults is absent. The progressive downward increase in offset of Upper Jurassic strata along some faults suggests, but does not prove, that fracturing in the zone commenced in middle Mesozoic time. Conversely, some of the largest faults offset strata as young as Early Cretaceous, and thus probably are at least as young as Late Cretaceous. In several places near the west edge of the district, faults are concealed by unfaulted landslide debris that is most likely of late Pleistocene age. Probably, the Dolores fault zone is latest Cretaceous or Tertiary in age, and, if related to accelerated growth of the Dolores anticline, is probably early to middle Tertiary in age. Like the faults along the collapsed Gypsum Valley anticline, those in the Dolores zone of faults could be of more than one age, or they may have been reactivated during more than one period of deformation. Unlike the Gypsum Valley faults, however, none of those in the Dolores zone of faults appear to be entirely devoid of alteration effects, showing that the zone developed largely before the period of alteration.

GLADE ZONE OF FAULTS

The Glade zone of faults takes its name from a prominent topographic feature—The Glade—in the southern part of the district, which is the surface expression of the Glade graben. The zone extends from southeast of the Disappointment syncline westward through the district and into Utah (fig. 2). The Verdure graben, at the south edge of the Abajo Mountains (10–15 miles west of the area shown in fig. 2), forms the west end of the zone. Although the orientation of the Glade zone of faults as a whole is about N. 80° E., individual faults within the zone strike between N. 55° W. and east, nearly parallel to individual faults along Gypsum Valley and in the Dolores zone of faults. Faults in the Glade zone are disposed en echelon, as though underlain by a right-lateral shear—that is, they show a gash-fracture relationship to an underlying shear, stepping to the left as a result of right-lateral shear.

Probably no more than about 300 feet of vertical movement has occurred on any of the faults in the zone, the largest, perhaps, in the Glade graben just east of the Dolores River canyon; most faults have had much less displacement. Although the Glade graben itself may seem to be a manifestation of incipient collapse of the Dolores anticline resulting from movement or dissolution of underlying salt in the core of the anticline, the graben appears not to be different from others in the en echelon zone. Formation of the other grabens more likely resulted from tension related to the inferred right-lateral displacement of the zone than from collapse over moving salt.

Faults in the Glade zone were examined in detail only at the Glade graben. There, most rocks that ordinarily show reddish colors have been bleached in the vicinity of the faults, indicating that faulting occurred before the period of structurally controlled alteration. In addition, faults and joints that bound the graben, and the rocks close to them, locally are heavily filled with hydrated iron oxides that may be alteration products of pyrite deposited during the period of alteration.

AGE OF THE GLADE ZONE OF FAULTS

Precise dating of the Glade zone of faults, like the other faults in the district, is impossible. The Glade zone is at least older than the main period of alteration and younger than the Mancos Shale of Late Cretaceous age which is cut by faults in the zone. An approximate minimum age of the zone is provided by relationships at the south edge of the Abajo Mountains in Utah, where the Verdure graben at the west end of the Glade zone controlled emplacement of igneous rocks. At that place the faults existed before intrusion (Witkind, 1964, p. 46), as shown by the presence of a laccolith that was intruded within the graben and confined by the bounding faults and by the presence of igneous dikes that lie along the bounding faults. The faults displace the Mancos Shale, indicating that faulting occurred at some time between the Late Cretaceous and the period of igneous activity in the Abajo Mountains. Witkind (1964, p. 81) considered the most likely age of the igneous rocks to be Late Cretaceous or Eocene. The Abajo Mountains rocks are petrographically similar to, and likely the same age as, those in the La Sal Mountains, which are estimated on the basis of isotope and potassium-argon data to be Miocene to possibly Eocene (23–55 m.y.) in age (Stern and others, 1965). The faulting probably occurred at the end of the Cretaceous Period or in the early part of the Tertiary.

MINOR FAULTS

A few faults of slight displacement lie in a northeasterly zone about normal to the Dolores zone of faults, passing near the town of Slick Rock. One fault is in Summit Canyon, two lie in the Lower Group of mining claims, and a few more are at the northeast edge of the district near Cape Horn (Shawe and others, 1968, pl. 1). No alteration was noted along any of these faults. Those in the Lower Group clearly have offset ore bodies in a uranium-vanadium deposit, and thus appear to be younger than the period of alteration and ore forma-

tion. They may correlate in age with postalteration faults in the zone of faults bordering Gypsum Valley.

JOINTS

Joints were mapped in detail in the northern part of the Slick Rock district, in the areas outlined in figure 5, mostly by W. B. Rogers, of the U.S. Geological Survey. Rather uniformly distributed joints occur in all rocks exposed throughout the district, although those in mudstone units are not well defined and therefore were not mapped. Soil cover also locally prevented mapping of joints.

Different types of sandstone units display somewhat different joint patterns. Massive units, such as the Entrada and Navajo Sandstones, may be fractured in zones separated by fracture-free areas as much as several hundred feet wide. Thinner bedded units, such as the Salt Wash Member, have fractures more regularly spaced; areas of unfractured rock are rarely more than 30 feet wide. Where beds of sandstone are separated by interbedded mudstone, the fractures in different sandstone beds are not continuous vertically but are interrupted by the mudstone beds, although they do maintain similar orientation in the separate beds.

Joint patterns in the district seem to be related to faults but not to major folds. Within 1.5 miles of the Dolores zone of faults on the northeast side, and within 4 miles on the southwest side, most of the joints strike between N. 45° W. and east, and in detail are parallel to individual faults; but differently oriented joints in this area also occur. Southwest of the town of Slick Rock a minor set of joints is oriented nearly north, whereas farther southeast a minor set has an orientation of about N. 45° E. Most joints farther than 1.5 miles northeast of the Dolores zone of faults are oriented nearly N. 20° E.; other orientations are common, but no other maxima are apparent. Joint patterns exhibit a change in orientation across a line, southwest of the town of Slick Rock, separating faults that trend about N. 60° W. and those that trend about N. 80° W. South of this line the orientation of the major joint set swings from easterly in the vicinity of Summit Canyon to southeasterly near the Dolores River canyon. North of this line the orientation of the major set swings from easterly west of Slick Rock to northeasterly north of Slick Rock. Possibly this difference in structural grain in two adjacent areas is related to an unrecognized deep-lying structure which separates the two areas and which is partly responsible for the minor set of northeasterly faults at the surface.

In general, none of the joint patterns appear to be oriented in a manner suggesting that conjugate sheer fractures formed from the compression of the folds.

If joints mapped in different formations are plotted on radial diagrams, they show different dominant orientations. For example, the dominant orientation of joints in the Burro Canyon Formation is about N. 20° E. (fig. 6), and in the Salt Wash Member of the Morrison Formation, almost east (fig. 7). This apparent difference probably can be explained by the fact that most joints mapped in the Salt Wash Member are closer to the Dolores zone or faults than those mapped in the Burro Canyon Formation.

A few joints in sandstone of the Burro Canyon Formation on the northeast side of the Disappointment syncline strike northwest and dip at a low angle to the southwest. Surfaces of these joints are locally iron stained.

AGE OF THE JOINTS

Some joints are bounded by altered rocks, proving that they formed before the period of alteration. Generally, joints oriented nearly parallel to the faults have influenced alteration, and probably these joints were formed at the time of faulting, near the end of the Cretaceous Period or at the beginning of the Tertiary Period. By analogy with the faults, the joints which are oriented nearly normal to the Dolores zone of faults and which did not localize alteration probably postdate the period of alteration and may be of middle to late Tertiary and Quaternary age.

Low-angle joints on the northeast side of the Disappointment syncline strike parallel to major folds and may have formed during folding. They are iron stained and thus apparently are older than the period of alteration.

Sandstone dikelets in the Navajo Sandstone along fractures striking about N. 30° W. in the area of the Dolores zone of faults may have formed when the Navajo was only partly consolidated, indicating that some fracturing occurred early in Jurassic time.

STRUCTURAL INTERPRETATION OF VARIATIONS IN FORMATION THICKNESSES

All the rocks of presumed Cambrian age thin toward the south and east (Shawe and others, 1968, p. A12), suggesting that the ancestral Zuni and Uncompahgre uplifts to the south and east, respectively, were structurally high during the early part of the Paleozoic Era.

Differences in thickness of Upper Devonian and Mississippian rocks throughout the Paradox basin (Baars, 1965; Shawe and others, 1968, p. A12–A14) reflect faulting and possibly folding during this period of deposition. Position and orientation of the salt anticlines are related to these thickness differences, which suggests that deformation commencing at least as early as

EXPLANATION

Kr

Rocks of Cretaceous age

Jm

Morrison Formation of Jurassic age

Jr

Rocks of Jurassic age and older

Fault

Nearly vertical joint

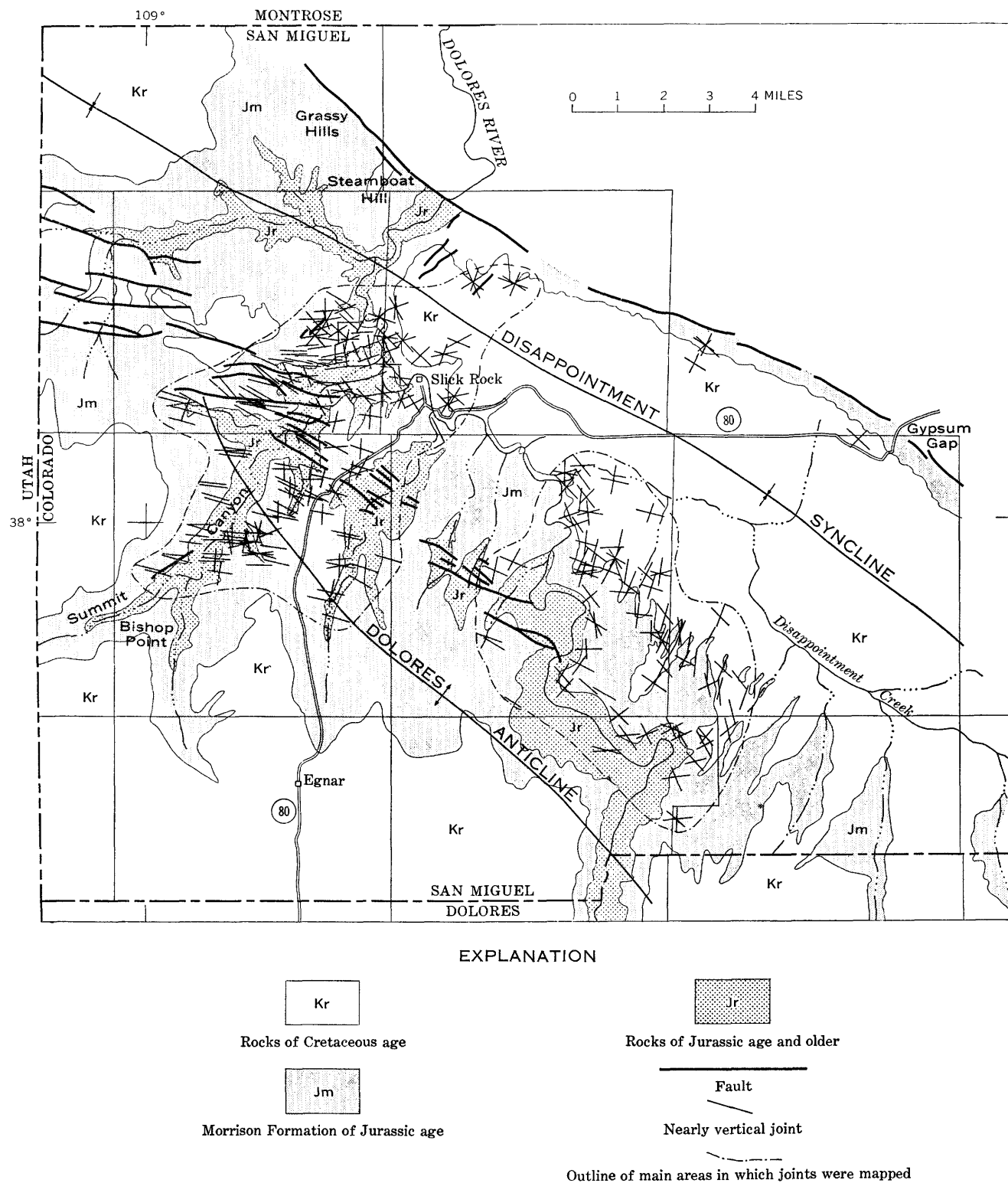Outline of main areas in which joints were mapped

FIGURE 5.—Map showing fracture patterns in parts of the Slick Rock district, Colorado. Joints mapped by W. B. Rogers and minor additions by N. L. Archbold, D. R. Shawe, and E. L. Boudette, 1954–56.
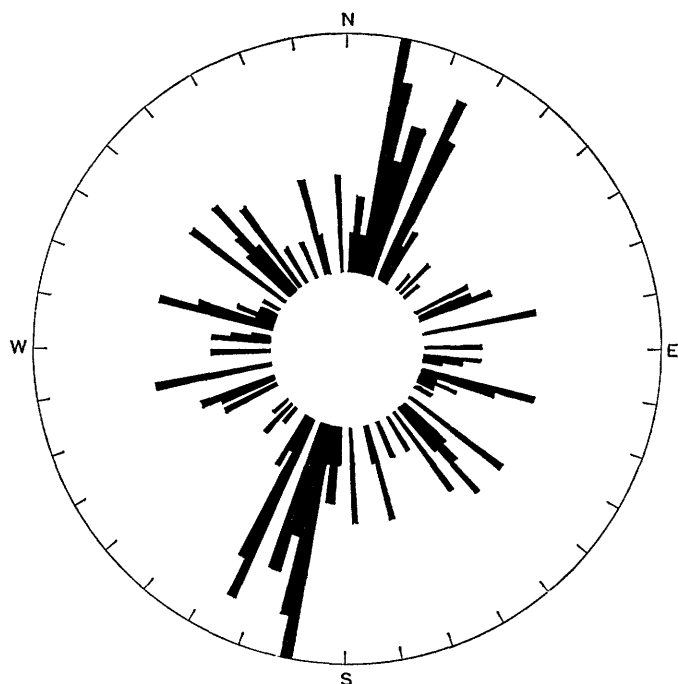
FIGURE 6.—Diagram showing orientation of 167 nearly vertical joints in the Burro Canyon Formation.
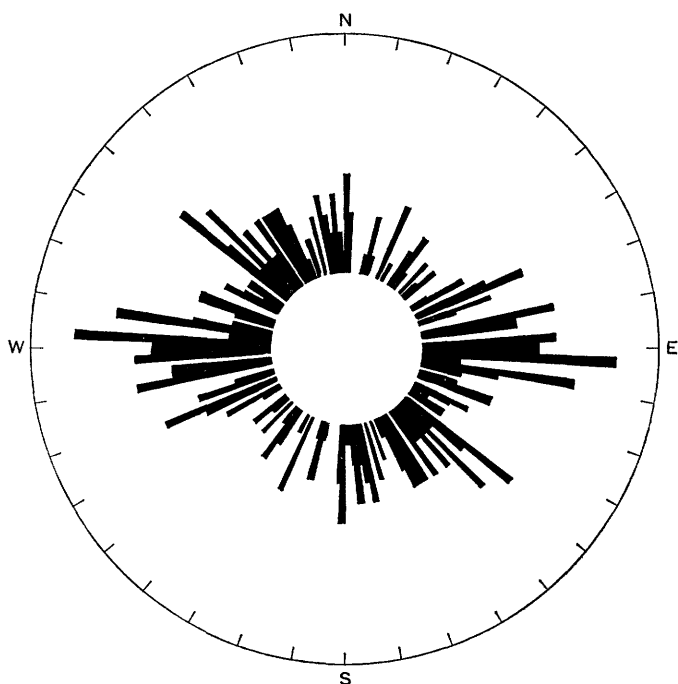

FIGURE 7.—Diagram showing orientation of 203 nearly vertical joints in the Salt Wash Member of the Morrison Formation.

Late Devonian time eventually controlled formation of the salt anticlines.

Trends of thickening and thinning in the Molas Formation and in the lower unit of the Paradox Member of the Hermosa Formation extending southwestward from the district (fig. 3) lie in or near a zone of deformation—the northeasterly trough in the Precambrian surface—initiated perhaps during Early Pennsylvanian time.

Salt thickening along anticlinal axes in the Paradox fold and fault belt has been thought by some workers to have resulted almost wholly from upward and lateral flow of salt of the Paradox Member of the Hermosa Formation induced by differences in specific gravity between salt and surrounding rocks (Stokes and Phoenix, 1948). However, the irregular base of the salt unit suggests that changes in the level of basement rocks, by faulting or perhaps by folding, may have been in part responsible for differences in thickness of the salt unit. Shawe, Simmons, and Archbold (1968, pl. 3, diagrams A, B, and E) showed that the base of the salt and, by inference, the top of the Precambrian basement complex are generally irregular. The base of the salt was likely virtually flat at the beginning of salt deposition. Now, however, where the base of the salt lies deeper, the salt is thicker and also rises higher than in surrounding areas, suggesting that salt thickening was directly related to local subsidence of the basement rocks during and after deposition.

Virtually all the stratigraphic units above the salt unit of the Paradox Member of the Hermosa Formation are thin above the Dolores anticline and thick in the Disappointment syncline, and are thin or pinched out around the Gypsum Valley anticline (Shawe and others, 1968, figs. 7, 8, 10, 12, 14, 15, 17, 26, 38, 40, 43). Folding, although undoubtedly sporadic, occurred throughout the time interval of Late Pennsylvanian—Late Cretaceous.

The northwesterly alinement of the isolated area of the Rico Formation in the vicinity of the Slick Rock district (Shawe and others, 1968, p. A22) leads to the interpretation that folding was responsible for the development of a local basin in which Rico rocks were deposited. Perhaps the occurrence of areas of presumed Rico Formation of different ages throughout the Paradox Basin and the difficulty in demonstrating physical continuity between these strata in different areas suggest that the Rico formed in isolated basins within the general area of Cutler Formation deposition (Shawe, and others, 1968, p. A22, A25) and that the basins did not form contemporaneously.

Thickness variations in a number of stratigraphic units of Late Pennsylvanian and younger age indicate periodic deformation along the northeasterly structural zone that passes through the south end of the Slick Rock district. Marked thinning of the upper unit of the Paradox Member of the Hermosa Formation and the Kayenta Formation is evident southeastward along a

"hinge line" parallel to, and a few miles southeast of, the northeasterly Glade subsurface fault zone (Shawe and others, 1968, figs. 7, 15). Trends of thickening of the upper unit of the Paradox Member of the Hermosa Formation, Cutler Formation, Moenkopi Formation, and Wingate Sandstone are alined with the zone (fig. 3). In addition, the Summerville Formation and Junction Creek Sandstone thicken southeastward from the northeasterly zone (Shawe and others, 1968, fig. 26, pl. 6, and p. A50).

Some evidence indicates that deformation of the northeasterly zone and folding of the Dolores salt anticline occurred simultaneously during certain times in the past. Trends of thickening of the Cutler Formation coincide with those of both the Disappointment syncline and the northeasterly structural zone (Shawe and others, 1968, fig. 10), proving that folding and deformation of the zone were concurrent. A local trend of thinning of the Chinle Formation occurs on the north side of the northeasterly trough in the Precambrian surface, and it coincides with an area where beds in the upper part of the Chinle were truncated by erosion before deposition of Wingate Sandstone (Shawe and others, 1968, fig. 12, and p. A31). Uplift and erosion occurred concurrently along the Gypsum Valley anticline, as suggested by thinning and pinchout toward Gypsum Valley of the Chinle below the Wingate (Cater, 1955a, c, d). The Wingate Sandstone shows similar relations (Shawe and others, 1968, fig. 14 and p. A35).

The flow of salt related to thickness variations of the Cutler Formation underlying the Disappointment syncline and adjacent anticlines probably did not take place as a result of overloading by Cutler detritus. According to F. W. Cater (written commun., 1960), salt rock under the physical conditions existing in the Paradox Member, confined under about 1,500 feet of the Hermosa Formation and an additional 2,000 feet of Cutler, probably did not flow plastically purely through load compression. Cater suggested rather that tectonic stresses were likely important in instigating confined flow of the salt, which accords with the evidence in the vicinity of the Slick Rock district. Kelley (1955, p. 74) and Hite (1968, p. 329) made similar suggestions.

Tremendous thickening of the Cutler adjacent to the Uncompahgre Plateau shows that the highland probably rose rapidly above the surrounding land. Possibly, the basin of Cutler accumulation sank as much as the highland rose, but even so, the sediments were not deposited under water. Deposition probably took place above land, just as detritus from the Sierra Nevada is being deposited subaerially in the California Valley today, although the base of the sediments has subsided thousands of feet below sea level.

The Moenkopi Formation was deposited upon an erosional surface of the Cutler Formation, and in turn the Chinle Formation was deposited upon an erosional surface of the Cutler and Moenkopi Formations. The oldest members of the Chinle Formation were deposited in western and southern Utah and in northern Arizona, and in a general way successively younger members were spread farther northeast, so that younger members are in contact with the underlying Moenkopi in that direction (Stewart and others, 1959, figs. 73, 81). These relations indicate development of a large depositional basin centered southwest of the Slick Rock district; this basin dominated sedimentation throughout much of the Mesozoic Era.

Before deposition of the Upper Jurassic Dewey Bridge Member of the Entrada Sandstone, a long period of erosion of the Navajo ensued from the Early or possibly Middle Jurassic. Thickness differences in the Navajo show that the Dolores anticline was raised in some places as much as 400 feet during this time, while erosion kept pace more or less with uplift. The resulting unconformity is widely recognized throughout the Colorado Plateau, and eastward from the Slick Rock district it is manifested by successively older formations beneath the Dewey Bridge Member (earthy siltstone member of the Entrada; Wright and Dickey, 1958, fig. 2). This transgression of strata indicates differential uplift of the region east of the district, before Entrada deposition.

The Junction Creek Sandstone and correlative units considered in their entirety (that is, the Junction Creek, the Bluff Sandstone in southeastern Utah, and the Cow Springs Sandstone in northeastern Arizona, Harshbarger and others, 1957, p. 48) probably represent development of a Late Jurassic basin in the general area lying between the south end of the Slick Rock district and the San Juan Mountains and extending into southeastern Utah and northeastern Arizona.

The Salt Wash Member of the Morrison Formation generally thickens to the southwest toward its source area in Arizona and southern California, but it is locally thick in the vicinity of the southeast end of the Paradox Basin. It is relatively thin above the Dolores and Gypsum Valley anticlines. During deposition of the lower and middle units of the Salt Wash Member, the Paradox Basin subsided; subsidence was accompanied by minor growth of the salt anticlines resulting in folding. During deposition of the ore-bearing sandstone, subsidence continued, perhaps more rapidly but without folding, so that a large fan or apron of reworked and winnowed sand was built eastward from the west end of the subsiding basin (Shawe, 1962, figs. 62.1, 62.2). The abundant fluvial sandstone and car-

bonaceous material at the toe of the apron in the vicinity of Slick Rock and the rest of the Uravan mineral belt provided a favorable lithologic environment that later helped localize the uranium-vanadium deposits.

The area of thinnest Salt Wash in the Slick Rock district clearly coincides with the axial region of the Dolores anticline, and is interpreted as an indication of the continuing folding of the region during Salt Wash time. Folding took place at the time of Salt Wash deposition inasmuch as the lower unit of the Salt Wash reflects the influence of the rising anticline and the middle unit indicates at least local uplift of the anticline. Probably no appreciable beveling by erosion of the Salt Wash took place before the Brushy Basin was deposited, for the relatively thin ore-bearing sandstone is everywhere present in the district, indicating that variations in thickness did not result from post-Salt Wash, pre-Brushy Basin folding. Distribution of sandstone-to-mudstone ratios in the Salt Wash was not influenced by the folding (Shawe and others, 1968, p. A52). The lack of correspondence of cumulative thinner sandstone with the axis of the anticline and cumulatively thicker sandstone with the axis of the syncline suggests that local folding at the time of Salt Wash deposition was not an important control of stream locations and consequently was not an important control of detritus distribution.

As interpreted from the regional configuration of the Salt Wash, the southeastern part of the Paradox Basin region was subsiding slightly during Salt Wash deposition, and hence subsidence corresponded in time with folding of the salt anticlines. A reasonable inference is that folding was causally related to basin subsidence.

During deposition of the Brushy Basin Member of the Morrison Formation, the area just south of Gypsum Valley at the boundary of Rs. 17 and 18 W., T. 44 N., (Shawe and others, 1968, fig. 40), appears to have been sinking more rapidly than surrounding areas. The greater thickness here of the Brushy Basin probably resulted from subsidence as evaporites flowed into the adjacent Gypsum Valley anticline. The local nature of the subsidence strongly suggests that the evaporite core of the Gypsum Valley anticline was growing largely at a salt cupola rather than throughout its whole length. The suggested cupola coincides in position with the large intrusive mass of the Paradox Member of the Hermosa Formation in T. 44 N., R. 17 W., and the NW cor. T. 43 N., R. 16 W., shown on the Hamm Canyon and Gypsum Gap geologic quadrangle maps by Cater 1955a, c). Possibly the thinner areas of Brushy Basin, about a mile west-southwest of the town of Slick Rock and in T. 42 N., and the SE cor. T. 43 N., R. 18 W.,

reflect minor growth of cupolas on the Dolores anticline (Shawe and others, 1968, fig. 40).

A great buildup of sandstone in the Brushy Basin Member near the axis of the Disappointment syncline (shown near the center of geologic section B, Shawe and others, 1968, pl. 12) may indicate that downfolding during deposition of the member controlled the main courses of streams. Fluvial deposition of coarser clastics dominated in the more rapidly sinking part, and flood-plain deposition of finer material occurred peripheral to this area.

The isopach map of the Brushy Basin published by Craig and others (1955, fig. 29) shows that the member is regionally thickest in two main areas. One area lies in the northern part of the Colorado Plateau, and the other occupies approximately the area of the Paradox Basin. The area of thick Brushy Basin coinciding with the Paradox Basin is significant here because it records a continuation of downwarping that occurred during Salt Wash time and because it was probably partly responsible for the continued folding of the salt anticlines. The Gypsum Valley anticline grew only locally in well-defined cupolas, but movement of salt may have been initiated by tectonism (compression?) that accompanied subsidence of the Paradox Basin.

The thicker part of the Brushy Basin Member in the area of the Paradox Basin thins to the southeast along a northeasterly axis (Craig and others, 1955, fig. 29). The axis coincides in position with the Glade subsurface fault zone. Again, faulting along this zone, depression of the Paradox Basin, and folding of the salt anticlines appear to have occurred simultaneously; therefore these three structural features may have been causally related.

Because the thickness variations of the Burro Canyon reflect those of the underlying Brushy Basin, their structural interpretation is similar, with an important exception. During the time Burro Canyon strata were being deposited, the Disappointment syncline deepened, probably as salt in the underlying Paradox flowed into a large salt cell in the Gypsum Valley anticline and to a lesser extent into a cupola on the Dolores anticline a few miles east of Egnar. Nevertheless, much of the thinning of the Burro Canyon away from Disappointment Valley must have occurred after deposition of the formation, for the Dakota was deposited unconformably on the Burro Canyon in this peripheral area and elsewhere.

The intertonguing between the Burro Canyon and the Brushy Basin as well as the similarity in sedimentation types in the lower part of the Burro Canyon and in the Brushy Basin hints that the depositional environment continued relatively unchanged from Brushy

Basin into Burro Canyon time. But the erosion of large areas of Burro Canyon, either late in Burro Canyon time or during the post-Burro Canyon—pre-Dakota time interval—indicates that Paradox Basin subsidence ceased near the end of Burro Canyon time. However, salt flow, having been induced by the tectonism, continued as a result of differential load stresses.

The lithologic character of rocks in the upper part of the Burro Canyon Formation indicates marginal or near-shore marine conditions, hardly compatible with elimination of the Paradox Basin. A suggestion of the effect of the Paradox Basin on deposition of Lower Cretaceous rocks is shown on an isopach map of strata of this interval in the Western United States by Reeside (1944). At the northeast boundary of a large area where Lower Cretaceous rocks are absent, a local extension of the rocks westward suggests that the Paradox Basin may have actively subsided following deposition of Lower Cretaceous strata.

The thicker part of the Dakota Sandstone almost certainly was deposited in a depression resulting from continued flow of evaporites from the axial region of the Disappointment syncline into the large salt cell occupying a segment of the Gypsum Valley anticline just to the northeast. This local movement of salt was already established at least as early as deposition of the Brushy Basin Member of the Morrison Formation, and it continued during deposition of the Burro Canyon Formation. Even though the salt flow must have been more or less continuous from Brushy Basin into Dakota time, it was likely interrupted after the Burro Canyon was deposited and before the Dakota was laid down. The evidence for this interruption is the widespread disconformity between those two formations and the abrupt change in lithology from the Burro Canyon to the Dakota, even in the Disappointment Valley area. Even so, conceivably, salt movement continued while the general land surface rose following deposition of the Burro Canyon Formation. General erosion prevailed and accounted for the widespread disconformity; but in the Disappointment Valley area, subsidence due to salt movement kept pace with the general uplift of the region, accounting for the preservation of most of the original Burro Canyon sediments in the synclinal basin and the generally conformable contact here between the Burro Canyon and the Dakota.

The Mancos Shale, like many older formations, shows by its thickness variations the influence of salt movement related to the growth of the salt anticlines. On the basis of the two known complete sections of the formation (Shawe and others, 1968, p. A91–A92), about 700 feet of structural relief developed on the base of the Mancos during Mancos time, between the axis of the

Gypsum Valley anticline and the axis of the Disappointment syncline. This amount is probably greater than the structural relief formed above the Dolores anticline, for the Gypsum Valley structure has been actively intruded by evaporites all through its history, which was not true for the Dolores anticline. The thickness variations in the unit of late middle Greenhorn age and those shown in higher strata in section A–A' (Shawe and others, 1968, pl. 1) suggest that the Disappointment synclinal axis was closer to the Gypsum Valley anticlinal axis in Late Cretaceous time than it is now, and possibly was alined more westerly than at present. The same relationships are shown for Dakota time, as indicated on the isopach map for that formation (Shawe and others, 1968, fig. 43). The fact that the synclinal axis lay rather close to the Gypsum Valley structure corroborates the theory that evaporite flow then was more active into the Gypsum Valley anticline than into the Dolores anticline.

Continued growth of the salt anticlines during deposition of the Mancos Shale is indicated by the differences in thickness of the formation related to the fold axes. Although this deformation had no apparent effect on the character of the Mancos sediments deposited in the salt anticline region, it formed significant structural relief between the Dolores anticline and the Disappointment syncline at that time.

SUMMARY AND CONCLUSIONS

A summary of the structural relationships in the Slick Rock district—in the context of regional structural elements—leads to a picture of interrelated faulting and folding throughout the depositional history of the Paleozoic and Mesozoic sedimentary rocks. This summary permits an interpretation of the influence of folds and fractures upon epigenetic alteration in the district and clarifies the time and manner of formation of the uranium-vanadium deposits.

Major folds are parallel to the northwesterly oriented Paradox Basin and to the Uncompahgre uplift at the northeast edge of the basin. The folds developed during depression of the basin and rise of the Uncompahgre element, showing their causal relationship.

The Dolores and Glade zones of faults are segments of regional alinements of faults (fig. 2). The Dolores zone of faults is an extension southeastward of the Lisbon Valley fault in Utah. This zone shows some evidence of grabenlike collapse above the salt core of the Lisbon Valley and Dolores anticlines. But the faults are deeper rooted than the underlying salt rock, as indicated by the 5,000 feet of stratigraphic displacement on the Lisbon Valley fault (Weir and Puffett, 1960, p. 134),

and by the stepped-to-the-right en echelon arrangement of small grabens in the zone in the Slick Rock district, indicating a deeper seated left-lateral shear.

The Glade zone of faults extends eastward from the Verdure graben in Utah (Witkind, 1964, fig. 14, p. 46) to faults lying east of the Slick Rock district. Its geographic position coincides closely with the postulated underlying Glade subsurface fault zone, which was shown to have been active during Paleozoic and Mesozoic time. The stepped-to-the-left en echelon disposition of grabens in the Glade zone of faults indicates that the controlling deep structure is a shear zone of right-lateral displacement.

Together, the Dolores and Glade zones of faults form a northwest-northeast conjugate system of lateral slip structures that reflect major structural trends in the region. This system probably has been active sporadically during most of Phanerozoic time.

Causal relationship between the northwesterly salt anticlines and the northeasterly Glade subsurface fault zone is plausible because they were deformed at times simultaneously. In addition, the presalt beginnings and northwesterly orientation of the folds and faults parallel to the Uncompahgre highland indicate that initiation and control of the folding and faulting were tectonic. Generally, compression or crustal shortening occurred northwest of the subsurface fault zone, in the region of the salt anticlines but not southeast of it, implying a component of strike-slip movement along the zone. If compression from the southwest, possibly buttressed against the Uncompahgre highland, accounted for flow of salt into the salt anticlines, strike-slip movement on the Glade subsurface fault zone was right lateral, in accord with the interpreted shear necessary to account for the observed stepped-to-the-left en echelon arrangement of the surface faults. Conversely, folding along northwesterly axes may be related to subsidiary up-and-down movements resulting from dominant northwesterly strike-slip faulting.

Small folds in the sedimentary rocks adjacent to Gypsum Valley appear to be related to intrusion of salt and collapse of overlying strata in the core of the salt anticline.

Joints in the Slick Rock district seem to be oriented mostly parallel to the fault sets, indicating a generic relationship and general contemporaneity.

Faults and joints in the Dolores and Glade zones of faults that are younger than strata of Late Cretaceous age controlled the movement of solutions that epigenetically altered the rocks. If periods of fracturing were correlated with accelerated folding of strata, as seems likely, it is inferred that the earliest significant post-

Late Cretaceous fracturing occurred during early to middle Tertiary time, possibly before the time of major uplift of the Colorado Plateau. Fracture-controlled alteration of rocks probably took place during the early to middle Tertiary. Evidence that uranium-vanadium mineralization was associated with the fracture-controlled alteration (Bowers and Shawe, 1961) indicates an early to middle Tertiary date for the mineralization. Subsequently, additional faulting and jointing occurred that was not accompanied by, or followed by, an episode of alteration; in fact, faults locally displaced mineralized rocks. Such fracturing was in part related to collapse of the salt anticlines, or to the late stage of growth of the Dolores anticline, during the late Tertiary and Quaternary.

It is noteworthy that faulting had started in the region surrounding the Slick Rock district early in the history of Paleozoic and Mesozoic sedimentation. It is likely, therefore, that significant faults existed in Jurassic and Cretaceous terrigenous clastic strata during the time of deposition of Upper Cretaceous marine Mancos Shale. After burial by the Mancos Shale, rejuvenation of these faults afforded a means by which part of the Mancos pore fluids were drawn off into underlying strata during load compaction of the shale, and these fluids may have effected alteration in the older rocks. This possibility will be examined in detail in a later chapter of this professional paper series, which will deal with alteration of the sedimentary rocks.

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