Regional Geophysical Investigations of the Moab-Needles Area, Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 516-C

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

REGIONAL GEOPHYSICAL INVESTIGATIONS
MOAB-NEEDLES AREA, UTAH

Aerial view of Upheaval Dome, San Juan County, Utah.

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GEOPHYSICAL FIELD INVESTIGATIONS

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Gravity and magnetic surveys of parts of Canyonlands National Park

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REGIONAL GEOPHYSICAL INVESTIGATIONS OF THE MOAB-NEEDLES AREA, UTAH

By H. R. Joesting,[1] J. E. Case, and Donald Plouff

ABSTRACT

Aeromagnetic and gravity surveys were made of about 1,450 square miles in the Moab-Needles area of Utah, in the north-central part of the Colorado Plateau. The area is within the Paradox evaporite basin, a subsurface feature of Pennsylvanian age. These surveys were made to gain broad-scale information on the depth, composition, and configuration of the Precambrian basement, and on major salt anticlines that may have influenced the occurrence of uranium, oil, and potassium-bearing evaporites.

Exposed sedimentary rocks range in age from Pennsylvanian to Recent. Cambrian, Devonian, and Mississippian rocks have been found in deep wells. No igneous rocks have been reported, and no Precambrian rocks have been penetrated by the drill.

According to geophysical evidence, the Precambrian rocks differ in magnetization and density, reflecting differences in composition. The sedimentary rocks are almost nonmagnetic, but their densities vary widely.

In the northern third of the area, which lies within the deeper part of the Paradox evaporite basin, magnetic gradients are low, thus indicating almost uniform magnetization of the basement. This magnetization does, however, increase gradually toward the northeast. In the southern third of the area, which includes the north end of the Monument uplift, the magnetic field is diverse, an indication of compositional diversity of the basement. In the central part, evidently a transition zone between basin and uplift, are three prominent magnetic highs, associated with large stocklike masses in the basement that are surrounded by rocks having about the same magnetization as those in the northern part. Upheaval Dome, a remarkable structural dome probably formed by an intrusive salt plug, is near the crest of one of the magnetic highs, but the high is at least four times as wide as the dome. No surface structural features are associated with the other magnetic highs.

The gravity anomalies are associated with density contrasts within both the Precambrian and the sedimentary rocks, particularly between the evaporites and the sandstone, shale, and limestone. Prominent lows occur over the large salt anticlines of Moab and Salt Valleys in the northern part of the area. Part of the anomaly along Moab Valley is evidently related to a basement fault that may have controlled the position of the salt anticline. A prominent gravity gradient in the central part of the area evidently marks a major lithologic and structural change in the basement: from lower density in the deeper basin to the north to higher density in the buried uplift to the south. Part of the gradient is also related to thinning of evaporites to the south. The deep-seated basement structural feature is also indicated by magnetic data. A gravity high in the southern part of the area is interpreted to be the result of comparatively dense basement and thinning of evaporites at the north nose of the Monument uplift. Regional lows near Meander anticline along the Colorado River may be associated with less dense or deeper basement and thicker evaporites.

Another major buried trough and its flanking structural highs, in the Mississippian and older rocks, trends northeast along the Colorado River. These structures are indicated by gravity and magnetic data and are partly corroborated by data from deep drilling. Minor rejuvenation of these features during Cenozoic time may have affected the course of the Colorado River.

INTRODUCTION

This report describes the results of aeromagnetic and regional gravity surveys in southeastern Utah in the area between Moab and The Needles, near the junction of the Green and Colorado Rivers (fig. 1). It is one of a series of regional geophysical studies of the Colorado Plateau, made to gain additional broad-scale information on the depth and configuration of the buried Precambrian basement, and on regional structures that may have influenced the occurrence of uranium, potassium-bearing salts, and oil (Joesting and Byerly, 1958; Byerly and Joesting, 1959; Case and others, 1963). The area discussed here includes The Knoll, Moab, Upheaval Dome, Hatch Point, The Needles, and Harts Point 15-minute quadrangles in parts of Grand, San Juan, Wayne, Garfield, and Emery Counties (fig. 1). The Canyonlands National Park lies partly within the area.

The Moab-Needles area is a land of broad high mesas and of deep precipitous canyons cut into multicolored sandstone and shale by the Colorado and Green Rivers and their tributaries. Upheaval Dome, a symmetrical structural dome into which a remarkably deep circular crater has been eroded (see frontispiece), is in the western part of the area. The Needles fault zone, with topography characterized by tall slender sandstone spires and valleys with interior drainage, lies in the southwestern part of the area just east of Cataract Canyon of the Colorado River and south of Meander salt anticline. Broad and elongate valleys have formed along

[1] Deceased, May 1965.

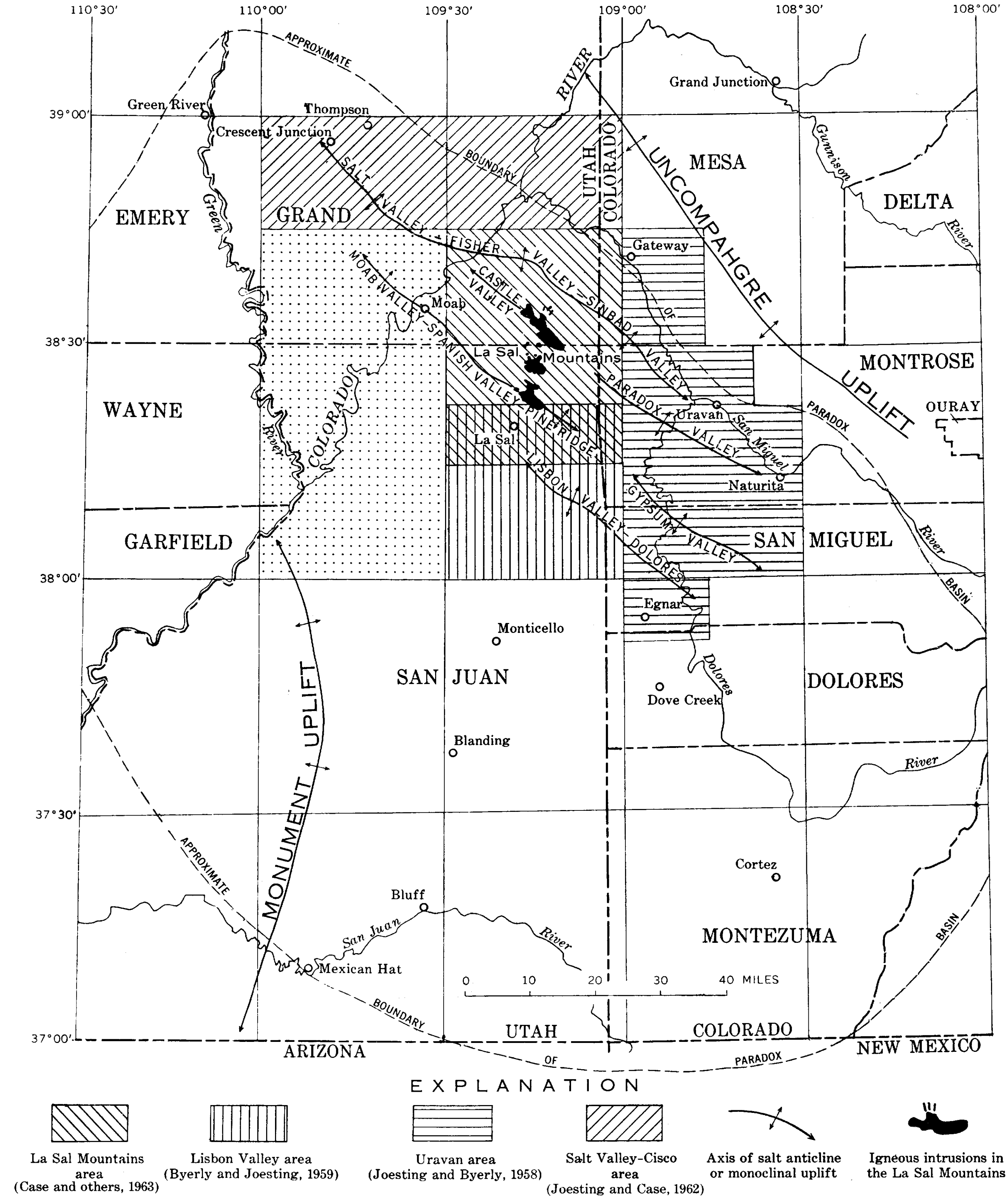

FIGURE 1.—Location of the Moab-Needles area (stippled) relative to major structures in the Paradox basin, Utah and Colorado.

the breached crests of Moab Valley and Salt Valley salt anticlines in the northeastern part of the area.

Airborne magnetic surveys were made over the area during 1954, and additional surveys were flown over Upheaval Dome in 1955. The airborne surveys were directed by J. L. Meuschke and R. W. Bromery; compilation of aeromagnetic data was directed initially by James Aubrey and later by Paul Yeager.

The gravity field party was initially under the direction of Richard Warrick; most of the fieldwork, however, was directed by Donald Plouff, assisted at various times by Winthrop Means, Jerome Marks, Marvin Bohannon, and Huntley Ingalls. A line of gravity stations was later established down the Green River by P. E. Byerly, and a line down the Colorado River to Cataract Canyon by J. E. Case. Ground magnetometer and gravity meter traverses and transit traverses for vertical control were run in Upheaval Canyon and from the rim to the bottom of Upheaval Dome by Joesting and Plouff and later by Joesting and Case.

Geologic information to aid in the interpretation of the geophysical data was obtained mainly from publications of Baker (1933, 1946), Dane (1935), and McKnight (1940), from oil-company drill logs and from oil scout reports. Information was also obtained from photogeologic maps of parts of the area by Bates (1955a, b, c), Bergquist (1955), Hemphill (1955), and Sable (1955a, b, c, and 1956); and from unpublished maps of parts of the Upheaval Dome and The Needles quadrangles by F. A. McKeown, P. P. Orkild, C. C. Hawley, and H. B. Dyer; of the Hatch Point, Harts Point, and of parts of the Upheaval Dome and The Needles quadrangles by E. N. Hinrichs; and of the southern part of The Needles quadrangle by R. Q. Lewis. Information on Paleozoic stratigraphy was contributed by Glen Ruby, consulting geologist; on Triassic stratigraphy by J. H. Stewart of the Geological Survey, and on regional structure by P. L. Williams, D. G. Wyant, and E. M. Shoemaker, also of the Geological Survey. Roland Henderson of the Geological Survey gave advice on estimating depths to sources of the magnetic anomalies.

Baker (1935), Kelley (1955), Shoemaker (1954), and others have published summaries of regional structural geology. Cambrian, Devonian, and Mississippian stratigraphy has been summarized by Cooper (1955), Cambrian stratigraphy by Baars (1958) and by Lochman-Balk (1956), and Devonian and Mississippian stratigraphy by Neff and Brown (1958). Pennsylvanian stratigraphy has been described by Wengerd and Matheny (1958), Wengerd and Strickland (1954), Wengerd (1958), Herman and Sharps (1956), and Herman and Barkell (1957).

Results of regional geophysical investigations by the Geological Survey in the salt anticline region were summarized by Joesting and Case (1960). More detailed reports were prepared on areas adjoining the Moab-Needles area: the Lisbon Valley area (Byerly and Joesting, 1959); the La Sal Mountains area (Case and others, 1963) to the east; and the Salt Valley–Cisco area (Joesting and Case, 1962) to the north (fig. 1). A brief preliminary report on geophysical investigations in the vicinity of Upheaval Dome was prepared by Joesting and Plouff (1958). A gravity map and brief discussion of the Moab-Needles area also was released (Joesting and others, 1962).

This investigation has been supported jointly by the U.S. Atomic Energy Commission and the U.S. Geological Survey.

GEOLOGIC SETTING

The Moab-Needles area is in the north-central part of the Colorado Plateau, in the Canyon Lands section of Fenneman (1931). The area is within the Paradox basin, which is characterized by thick Pennsylvanian evaporites that locally form the cores of salt anticlines (fig. 1). Structure of sedimentary rocks at the surface, however, gives no hint of the buried Pennsylvanian basin; the exposed rocks dip gently northward and northeastward from the Monument uplift, in the southern part of the area, toward the Uinta Basin, which lies farther north. A deep-seated fault or other vertical displacement within the Paradox basin, trending west-northwest across the area, divides the basin into a shallower southern part and a deeper northern part.

Sedimentary rocks exposed in the Moab-Needles area range in age from Pennsylvanian to Recent. Permian, Triassic, and Jurassic rocks crop out over most of the area, but Cretaceous rocks are confined to the northern part of the area near Courthouse syncline and in Salt Valley (pl. 1.) Pennsylvanian rocks are exposed in the deeper canyons and in some of the breached salt anticlines. Cambrian, Devonian, and Mississippian rocks have been penetrated by deep wells. A generalized geologic column is shown in table 1.

As far as is known, the sedimentary rocks in the Moab-Needles area are virtually nonmagnetic and have no effect on the airborne magnetometer. Anomalies shown on the magnetic maps (pls. 2, 3) presumably originate in the diversely magnetized rocks of the Precambrian basement, as igneous rocks younger than Precambrian have not been found in the area. On the other hand, both the crystalline Precambrian rocks and the overlying sedimentary rocks vary widely in density, so that the gravity anomalies (pl. 4) are associated with contrasts in density of various lithologic units in both the crystalline and sedimentary rocks, and with their dimensions and depth beneath the surface.

TABLE 1.—*Generalized geologic column*

[Data from Baker (1933), McKnight (1940), Cooper (1955), Baars (1958), Neff and Brown (1958), Wengerd and Matheny (1958), Wengerd (1958) and logs of drill holes prepared by American Stratigraphic Co., Denver, Colo.]

System	Stratigraphic unit	Thickness (feet)	Lithology	Estimated density (g per cm ^{3})
Quaternary		0–500?	Alluvial sand, silt, and gravel, talus, and windblown deposits.	2.2–2.4
Cretaceous	Mancos Shale	2,500?	Shale and siltstone	2.3–2.45
	Dakota Sandstone and Burro Canyon Formation.	200?	Sandstone and conglomerate	
Jurassic	Morrison Formation	540–850	Shale, siltstone, sandstone, and conglomeratic sandstone.	
	San Rafael Group: Summerville Formation, Curtis Formation, Entrada Sandstone, and Carmel Formation.	400–750	Sandstone and siltstone	
Jurassic and Triassic	Glen Canyon Group: Navajo Sandstone, Kayenta Formation, and Wingate Sandstone.	550–1,100	Sandstone and siltstone	2.3–2.5
Triassic	Chinle Formation and Moenkopi Formation	0–1,600?	Shale, siltstone, sandstone, and conglomerate	
Permian	Cutler Formation	0–1,000	Arkosic sandstone, quartzose sandstone, and shale.	
Permian and Pennsylvanian	Rico Formation	0–300?	Limestone, shale, and arkosic sandstone	2.58–2.65
Pennsylvanian	Hermosa Formation: Upper member	900–1,500	Limestone, shale, and sandstone	
	Hermosa Formation: Paradox Member	2,000–4,000	Salt, gypsum, black shale, and limestone	2.2–2.3?
	Hermosa Formation: Lower member	0–200	Limestone and shale	
	Molas Formation	0–150	Shale, sandstone, and limestone	2.6–2.7
Mississippian, Devonian, and Cambrian		1,500–2,500	Limestone, shale, dolomite, and sandstone	
Precambrian			Granite(?), schist(?), and gneiss(?)	2.7–3.0?

Principal structural features include the Salt Valley, Moab Valley, and Cane Creek salt anticlines in the northern part of the area (fig. 1, pl. 1), smaller anticlines or domes, including Upheaval Dome, Shafer Dome, Lockhart anticline, Gibson Dome, and Rustler Dome in the central part of the area, and Meander anticline and The Needles fault zone in the southern part. These features are superimposed on the northward regional dip between the Monument uplift and the Uinta Basin. Total structural relief in the region is about 5,000–6,000 feet, measured on a Cretaceous horizon (Williams, 1964).

STRATIGRAPHY

PRECAMBRIAN

Precambrian rocks have not been penetrated by wells within the Moab-Needles area. To the east, on the southwest flank of Lisbon Valley salt anticline (fig. 1), a coarse-grained pink biotite-quartz monzonite was reached at about 2,700 feet below sea level in the Pure Oil Co. NW. Lisbon-U.S.A. 2–A well. Coarse granitic rock was also reached at 4,668 feet below sea level in the Shell Oil Co. Wray Mesa 1 well, on the southwest flank of Paradox Valley anticline. To the west, biotite granite was penetrated in wells on the San Rafael Swell. Precambrian rocks exposed on the Uncompahgre Plateau to the east include several varieties of granite, several varieties of quartzo-feldspathic gneiss, biotite schists, amphibolites, and metagabbro (Dane, 1935; Cater, 1955; McKay, 1955; Shoemaker, 1956; Case, 1966). These rocks vary widely in density and magnetic susceptibility (Case, 1966). Judged from their associated magnetic and gravity anomalies the Precambrian rocks in the Moab-Needles area appear to have a comparable range in density and magnetic susceptibility.

The approximate magnetic and mass properties of Precambrian rocks in the Moab-Needles area may be estimated by analysis of the magnetic and gravity maps (pls. 2–4), and by comparison with geophysical anomalies over Precambrian rocks exposed in the uplifted regions bordering the Colorado Plateau. The magnetic map shows that the basement rocks are of uniform magnetization in the northern part of the area and of diverse magnetization in the southern two-thirds of the area. The estimated range in magnetic susceptibility of the basement rocks, discussed on page C11, is on the order of 0.004 cgs units, which is the approximate range found in specimens of Precambrian rocks from the Uncompahgre uplift (Shoemaker, 1956, p. 57; Joesting and Byerly, 1958, p. 2–4; Case, 1966).

The generally uniform and moderate magnetization of the basement rocks in the northern third of the area is more evident on plate 3 because the latitude gradient, or northward increase in dipole intensity, has been removed. Generally uniform magnetization is characteristic of the basement in deeper parts of the Paradox basin, in striking contrast to the diverse magnetic pattern in the uplifts (Joesting and Byerly, 1958, p. 8–12). The uniform magnetization suggests that the deeply buried basement may consist of metamorphosed sedimentary rocks, as the magnetization of igneous rocks is commonly more varied. However, inasmuch as granitic rocks were found in a similarly uniform magnetic environment in deep wells at Lisbon Valley and Wray Mesa, some 40 miles to the southeast, granitic rocks may also underlie the deeper, northern part of the Moab-Needles area.

Despite diverse magnetization of basement rocks in the southern two-thirds of the area and comparative uniformity in the northern third, the average magnetization is about the same in the whole area (pl. 3). The pattern in the southern two-thirds of the area is that of a Precambrian basement of low, uniform magnetization into which rocks of higher magnetization have been intruded. This diverse pattern is characteristic of Precambrian rocks of major uplifts of the Colorado Plateau.

Densities and density contrasts of the basement rocks are more difficult to estimate than magnetic susceptibility contrasts, because the gravity anomalies result from contrasts in the densities of both basement rocks and the overlying sedimentary rocks. To reproduce the observed gravity profile at Upheaval Dome and Grays Pasture, for example, it was necessary to assign several densities to the basement and sedimentary rocks. (See p. C14.) These values for density are based in part on assumptions concerning contrasts in thicknesses and densities of the overlying rocks (table 1). There is no direct information on the basement rocks, although the assigned densities of 2.7–3.0 g per cm^3 are in agreement with measured densities of basement rocks from uplifted areas surrounding the Colorado Plateau (Shoemaker, 1956, p. 57; Joesting and Byerly, 1958, p. 8–12; Case, 1966).

CAMBRIAN, DEVONIAN, AND MISSISSIPPIAN

Rocks of Cambrian age range from 800 to 1,200 feet in thickness in the area and include limestone, dolomite, and sandstone (Cooper, 1955, p. 59–61; Lochman-Balk, 1956, p. 63–64; Baars, 1958, p. 93–101). Devonian rocks range in thickness from about 300 to 600 feet. They include dolomite, limestone, shale, and sandstone, with carbonate rocks predominating (Cooper, 1955, p. 61–63; Neff and Brown, 1958, p. 102–103, exhibit III). Mississippian rocks range in thickness from 500 to 700 feet. They consist mainly of carbonates with very little associated clastic material (Cooper, 1955, p. 63–65; Neff and Brown, 1958, p. 102–105). These rocks all thicken toward the western and northwestern parts of the area; their aggregate thickness is about 1,500–2,500 feet. Their estimated density is about 2.6–2.7 g per cm^3—somewhat higher than that of the Mesozoic rocks because the Paleozoic rocks are comparatively well indurated and contain a high proportion of carbonates (Case and others, 1963, p. 93–94).

PENNSYLVANIAN

MOLAS FORMATION

The Molas Formation is a sequence of red beds, in part regolithic—shale, sandstone, and limestone. It is 0–150 feet thick in the Paradox basin (Wengerd and Matheny, 1958, p. 2064). Although a useful stratigraphic marker in deep wells, it has no bearing on the interpretation of the geophysical anomalies because it is relatively thin.

HERMOSA FORMATION

The Hermosa Formation comprises a lower limestone member, the (middle) Paradox Member, and an upper limestone member (Bass, 1944). The Paradox Member is the most significant sedimentary unit in the Moab-Needles area with respect to interpretation of the gravity data, because it consists largely of low-density evaporites that locally form the thickened cores of the salt anticlines.

Thickness of the lower limestone member (Pinkerton Trail Formation of Wengerd and Strickland, 1954, p. 2168–2169) is about 0–200 feet in the area (Wengerd and Matheny, 1958, fig. 14, p. 2086). About 60 feet of limestone found in the Midwest Exploration Co. J. H. Shafer 1 well on Shafer Dome was assigned to the Pinkerton Trail Formation by Wengerd and Strickland (1954, p. 2168–2169). This unit is too thin to have appreciable effect on the gravity data.

The evaporitic Paradox Member (Paradox Formation of Wengerd and Strickland) ranges in thickness from about 1,500 to 4,000 feet where undisturbed by plastic flow (Wengerd and Matheny, 1958, fig. 15). It is 2,500–3,675 feet thick in wells drilled near the northwest end of the Cane Creek anticline, about 5,200 feet thick in the Modco, Inc., M.G.M. 1 well drilled near the Colorado River on the Cane Creek anticline, and more than 7,000 feet thick in the Delhi Oil Co. Utah 2 well on the Moab anticline. In these anticlines the evaporites have thickened because of flowage. The evaporites are about 3,000–3,500 feet thick at Big Flat near the northwest end of the Cane Creek anticline, where structural relief is small and where they presumably have been little disturbed. Farther south, toward Upheaval Dome and Grays Pasture, drilling indicates that they are thinner, because of plastic flow and (or) nondeposition.

The Paradox Member is about 70–75 percent salt; the remaining material, where penetrated by drilling in the Moab, Cane Creek, and Shafer anticlines, is shale, gypsum, anhydrite, and limestone (Shoemaker and others, 1958, p. 47). The density of the member is computed as about 2.2 g per cm^3, if minor effects of porosity are disregarded. Contrasts in density of the evaporite member with adjacent denser sedimentary rocks, therefore, provide the largest within the sedimentary section.

The upper member of the Hermosa Formation (Honaker Trail Formation of Wengerd and Matheny, 1958) is about 900–1,500 feet thick in the area (Wengerd and Matheny, 1958, fig. 17). The Hermosa generally thickens toward the northeast. The probable range in density of the limestone members of the Hermosa Formation is about 2.58–2.62 g per cm^3, similar to that in the Lisbon Valley area (Byerly and Joesting, 1959, p. 41).

PENNSYLVANIAN AND PERMIAN

RICO FORMATION

The Rico Formation is composed of alternating beds of sandstone and arkose, with subordinate limestone and shale; its thickness is about 400–600 feet (Baker, 1933, p. 24–25; 1946, p. 33; McKnight, 1940, p. 25–36). The formation is included with the Hermosa Formation on the geologic map (pl. 1).

PERMIAN

CUTLER FORMATION

The Cutler Formation is widely exposed in the canyon walls and benches of the Green and Colorado Rivers and underlies most of the southwestern part of the area. It is mainly sandstone and siltstone, and its total thickness ranges from 670 feet in Lockhart Canyon to more than 1,000 feet in the southern part of the area (Baker, 1946, pl. 7; 1933, p. 30–31). The Cutler Formation thins markedly over the crests of the salt anticlines.

MESOZOIC

Rocks of Mesozoic age are exposed over most of the eastern and northern parts of the area. They include, from oldest to youngest, the Moenkopi and Chinle Formations and Wingate Sandstone of Triassic age; the Kayenta Formation of Triassic(?) age; the Navajo Sandstone of Triassic(?) and Jurassic age; the Entrada, Carmel, Curtis, Summerville, and Morrison Formations of Jurassic age; and the Burro Canyon Formation, Dakota Sandstone, and Mancos Shale of Cretaceous age. These formations are for the most part continental deposits, except for the Mancos, which is marine. Their aggregate thickness is about 3,500–4,500 feet, not including the upper part of the Mancos, which is not present in the area (table 1).

The Mesozoic rocks probably range in density from 2.4 to 2.5 g per cm^3, as they are generally similar in lithology to Mesozoic rocks in the Uravan and Lisbon Valley areas where the density of rocks in the interval between the Chinle and Navajo, based on gravity measurements at the top and bottom of San Miguel Canyon near Uravan, Colo., was found to be about 2.5 g per cm^3 (Joesting and Byerly, 1958, p. 5).

QUATERNARY

Unconsolidated Quaternary deposits of sand and gravel are absent or relatively thin ($<$ 50 ft) over most of the area except at Moab Valley, where alluvium may be locally several hundred feet thick. These deposits have little effect on interpretation of the geophysical surveys.

METHODS OF CONDUCTING GEOPHYSICAL SURVEYS

Aeromagnetic and gravity surveys conducted in the Moab-Needles area were generally similar to surveys carried out in the adjoining Lisbon Valley area (Byerly and Joesting, 1959, p. 43–44) and in the La Sal Mountains area (Case and others, 1963, p. 99–100).

East-west magnetic traverses were flown 1 mile apart over the area at about 8,500 feet above sea level. A more detailed survey was flown over Upheaval Dome at a barometric altitude of 7,500 feet. The surveys were made with a continuously recording AN/ASQ–3A fluxgate magnetometer installed in a two-engine aircraft flying at about 150 miles per hour. Aeromagnetic maps were compiled according to procedures described by Balsley (1952).

Gravity stations were spaced at 1- to 2-mile intervals, mainly along roads and trails over much of the area.

Spacing was closer in the vicinity of Upheaval Dome and much wider in The Needles region in the southern part of the area, where access is difficult. A total of 565 gravity stations, including 38 base stations, was established in the approximately 1,450-square-mile area.

Locations of stations were plotted on 7½-minute topographic maps at a scale of 1:24,000. Elevations of most stations were determined by altimeter surveys, although bench marks and photogrammetric elevations were used where available. Errors of 10–20 feet, and greater in some places, are probably inherent in elevations obtained by altimeters. Photogrammetric elevations are assumed to be correct within one-half contour interval, or 20 feet. Bench-mark elevations are correct within 1 foot.

Terrain corrections through zone "J" of Hammer's tables (1939) were applied at many stations. The largest corrections were of course required for those stations in the floors of the deep canyons and at canyon rims. Terrain corrections in the crater of Upheaval Dome, for example, were as large as 8 mgal (milligals); in the Colorado River canyon below its junction with Green River they were as large as 11 mgal.

In general, the overall error in gravity values at individual stations is estimated to be less than 2 mgal. The order of accuracy is, therefore, somewhat lower than that of regional gravity surveys in the Uravan area of Colorado (Joesting and Byerly, 1958) and in the adjoining Lisbon Valley area of Utah and Colorado (Byerly and Joesting, 1959), because of poorer elevation control, and is somewhat higher than that in the adjoining La Sal Mountains area (Case and others, 1963) because of better elevation control.

Principal facts for gravity stations in the area have been placed on open file (Joesting and others, 1963).

INTERPRETATION OF THE MAGNETIC MAPS

For the most part, anomalies shown on the magnetic maps (pls. 2, 3) are associated with contrasts in the magnetization of the Precambrian basement rocks. These contrasts in turn depend predominantly on contrasts in the content of magnetite and related ferrimagnetic minerals, and probably to a lesser degree on variations in the intensity and direction of remanent magnetization. In general, the anomalies—at least the prominent, well-defined ones—are also assumed to indicate contrasting basement rocks which have relatively sharp rather than gradational boundaries.

The northern third of the magnetic map is characterized by comparatively low gradients and is virtually free from closed contours. The central part is dominated by three prominent nearly circular highs—at Upheaval Dome, at Grays Pasture, and just north of Hatch Point—in an area of otherwise low gradients and comparatively low magnetic intensity. The southern third of the map is characterized by a number of moderately prominent, rounded highs and lows. Removal of the prominent local highs and lows in the southern two-thirds of plate 3 leaves a regional or "background" magnetic field that does not vary greatly in intensity over the whole area.

Regional magnetic trends are northwestward and westward in the northern two-thirds of the area, generally parallel to regional structural trends at the surface. No analogous alinement of magnetic and structural trends is evident in the southern third of the area, which includes the north end of the north-plunging Monument uplift.

Crossing the northwesterly and westerly regional magnetic trends is a prominent northeast magnetic trend, represented by the locus of termination of magnetic anomalies, which follows the Colorado River from Cataract Canyon to Kane Springs Canyon and is also alined, perhaps coincidentally, with Meander anticline and associated structures at Cataract Canyon. This trend of anomalous magnetization evidently marks the position of an ancient basement structural feature with attendant contrasts in the magnetization of the Precambrian rocks (Case and Joesting, 1962).

Recent deep drilling to Mississippian and older rocks in the Big Flat area and farther southeast reveals a large asymmetric structural trough coincident with the Colorado River; the area southeast of this trough is apparently higher than the area to the northwest (fig. 2). The southwest extent of this trough is not known. The apparent left-lateral displacement of the Hatch Point magnetic anomaly with respect to the Grays Pasture and Upheaval Dome anomalies is probably significant in respect to extent of the trough; these displaced anomalies may be related to an equivalent displacement of magnetic basement rocks. In addition, termination of the Lockhart salt anticline and the Rustler and Gibson salt domes at the Colorado River may indicate thinner salt northwest of the river and to the southeast, possibly because of structural uplift, and local depositional thickening of salt in the trough.

The reason for the remarkable alinement of the Colorado River and Meander anticline with the northeastward magnetic trend and with the indicated basement structure is not known. The structure is apparently reflected in Mississippian and older Paleozoic rocks, but not in the younger Paleozoic and Mesozoic rocks exposed at the surface, although the surface rocks a few miles southeast of the river are displaced by small northeast-striking faults (pl. 1). The position of the river may have been controlled by minor rejuvenations

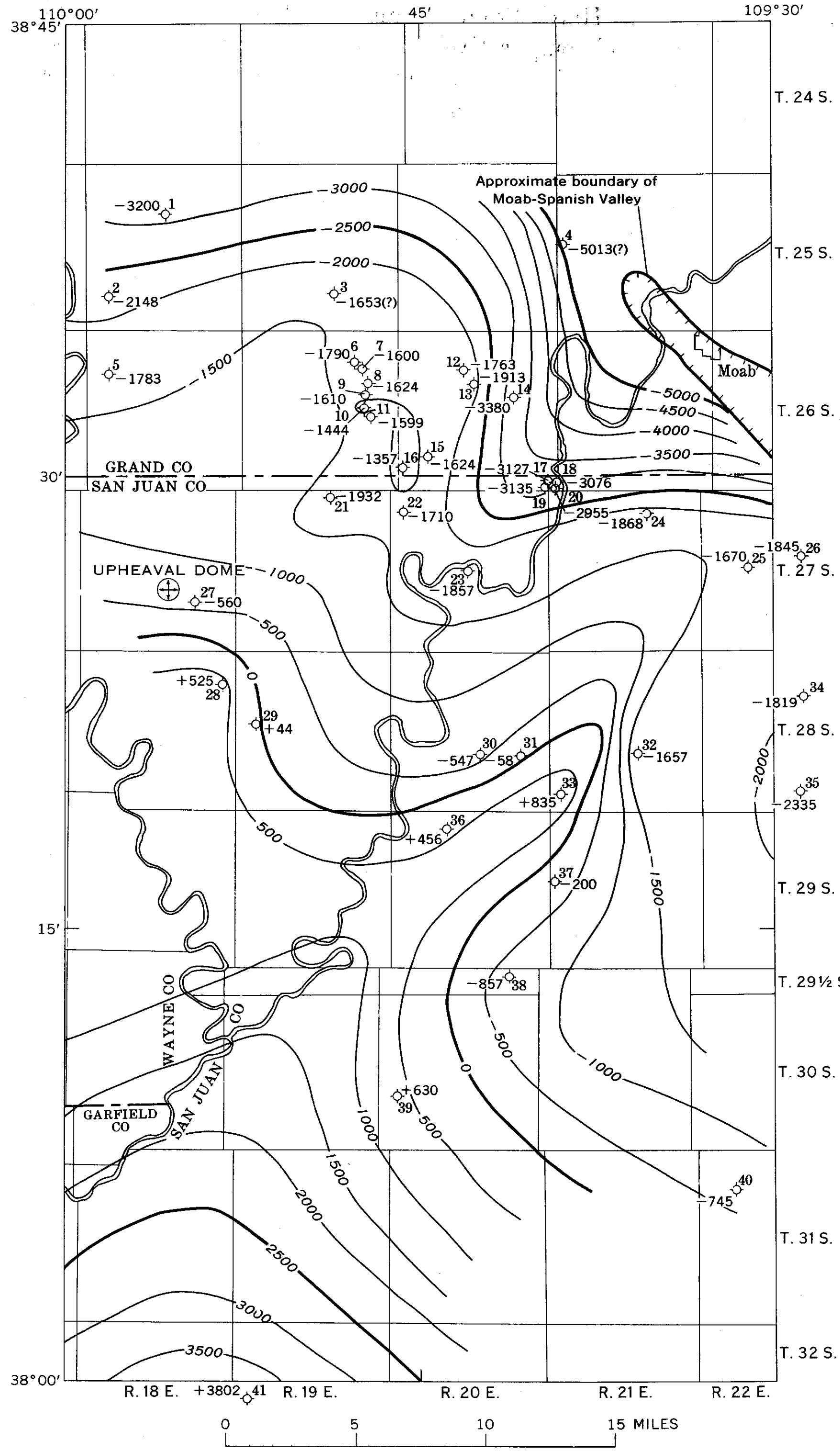

FIGURE 2.—Inferred configuration of the Mississippian surface in the Moab-Needles area.

EXPLANATION

—2000—
—2500—

Structure contours

Drawn on the top of Mississippian rocks. Contour interval 500 feet. Datum is mean sea level

34 −1819

Drill hole

Showing elevation of top of Mississippian rocks; queried where identification of top uncertain

LIST OF DRILL HOLES

1. McRae Oil and Gas Co. McRae-Federal 1
2. Federal Oil Co. Federal-Bowknot 1
3. Pure Oil Co. Big Flat Unit 5
4. Delhi Oil Co. Utah 2
5. Pure Oil Co. U.S.A. Mineral Point 1
6. Glen M. Ruby Unit 1
7. Tidewater Associated Oil Co. Big Flat Unit 74-11
8. King Oil Co. Ruby 2
9. Pure Oil Co. Big Flat Unit 2
10. Pure Oil Co. Big Flat Unit 1
11. Pure Oil Co. Big Flat Unit 3
12. Southern Natural Gas Co. Unit 1
13. Southern Natural Gas Co. Unit 2
14. Jay Roberts White Cloud 1
15. Murphy Corp. Little Valley Unit 1
16. Cabeen Exploration Co. Big Flat-Government 1
17. Transcontinental Oil Co. M.G.M. 2
18. Transcontinental Oil Co. Texas Gulf-Federal 1
19. Modo, Inc., M.G.M. 1
20. Mason Oil Co.-Modoc, Inc., M.G.M. 2
21. British-American Oil Producing Co. Federal-Ormsby 1
22. Southern Natural Gas Co. U.S.A. 2
23. Midwest Exploratoin Co. J. H. Shafer 1
24. Humble Oil and Refining Co. West Bridger Jack Unit 3
25. Humble Oil and Refining Co. Bridger 1
26. E. B. La Rue Government 1
27. Husky Oil Co. Buck Mesa 1
28. Pan American Petroleum Corp. Murphy Range Unit 1
29. Shell Oil Co. Murphy Range 1
30. Gulf Oil Corp. Aztec-Lockhart-Federal 1
31. Pan American Petroleum Corp. U.S.A-Lockhart 1
32. Richfield Oil Corp. Hatch Mesa 1
33. Pan American Petroleum Corp. Charles 1
34. Pure Oil Co. Flat Iron 1
35. Cities Service Oil Co. Government 1-B
36. Humble Oil and Refining Co. Rustler Dome 1
37. Pure Oil Co. Horsehead 1
38. Reynolds Mining Co. Gibson Dome 1
39. Pure Oil Co. Test Canyon 1
40. Gulf Oil Corp. Hart Point 1
41. Texaco, Inc., Cataract Canyon 2

of the ancient structure during Cenozoic time, when the course was established. If so, the resulting displacements at the surface are too small to show in the structural contours drawn on the base of the Dakota Sandstone (pl. 1). Although a broad structural high is approximately coincident with the river course, the 500-foot contour interval, in fact, may be much too coarse to show the comparatively small displacements that might be adequate to influence the course of the river. At present, then, we can only call attention to the apparent coincidence of the prominent regional northeastward magnetic trend with a deep-seated structure and likewise to the coincidence, for more than 100 miles, of the magnetic trend with the remarkably straight course of the Colorado River.

Except as already mentioned, there is little apparent relation between the configuration of the magnetic pattern and the structural pattern of the rocks exposed at the surface. Magnetic and structural highs coincide at Upheaval Dome, but the magnetic high is much broader, and any relationship to the domal structure is indirect. The anomalies at Grays Pasture and Hatch Point show no correlation with surface structural features, although they are similar in appearance, and probably in origin, to the Upheaval Dome anomaly.

NORTHERN PART OF AREA

A remarkable feature shown by the magnetic map is the almost uniform increase in magnetic intensity of 200–400 gammas to the north and east in the northern part of the area, where the Precambrian rocks are more deeply buried. This comparatively uniform gradient is in striking contrast with the diverse magnetic pattern of the remainder of the area. The gradient is evidently related in part to a gradational northeastward increase in magnetization of the Precambrian basement in the northern third of the area, and in part to the latitude effect, or northward dipole increase in the earth's magnetic intensity. On plate 3 the latitude effect, estimated to be 9.1 gammas per mile along the magnetic meridian, has been removed. There remains a positive northeastward and eastward gradient, totaling roughly 100 gammas in 25 miles, which must be attributed mainly to a gradational or regional increase in magnetization of basement rocks. Similar rather uniform gradients, positive to the north and northeast, are also associated with the deeper parts of the Paradox basin in the nearby Uravan and Salt Valley–Cisco areas (Joesting and Byerly, 1958, p. 9–11; Joesting and Case, 1962, p. 1885). The magnetic irregularities and the single small-amplitude high superimposed on the regional northeastward gradient reflect small local variations in magnetization of the basement, rather than regional effects.

Causes of the comparatively uniform northeastward increase in magnetic intensity can only be surmised. The possibilities are: a gradational increase in ferrimagnetic mineral content of the Precambrian basement, a gradational increase in thickness of a uniformly magnetic upper part of the basement, or presence of a magnetic differentiate at great depth within the basement. More than one cause could, of course, contribute to the increase. The possible causes listed are not amenable to quantitative analysis, as no direct information on basement composition is available in the Moab-Needles area. Steeply inclined boundaries separating rocks of contrasting magnetization are considered unlikely, except possibly at great depths within the basement, because there are no sharp changes in magnetic gradients. The most likely cause of the uniform increase in magnetic gradient is a gradational increase in the ferrimagnetic content of the basement.

A gradational change in ferrimagnetic minerals could be related to comparable variations in original composition, or to various degrees of metamorphism of basement rock that was originally magnetically uniform. Gradational variation in original composition could result from deposition of detritus eroded from the comparatively magnetic crystalline rocks of an uplifted ancestral Uncompahgre Plateau of Precambrian age. Some sorting and preferential deposition of heavy magnetic minerals close to the uplift would be required. This mechanism seems to be inadequate, however, because the magnetic susceptibility of the arkosic Cutler Formation close to the Uncompahgre structural front is very low (Joesting and Byerly, 1958, p. 5). The Cutler Formation was derived from cystalline rocks of the ancestral Uncompahgre Plateau during a late Paleozoic uplift, under the same conditions that would probably have existed during the postulated Precambrian uplift. A gradational differentiation in original composition of a basement rock of magmatic origin also seems unlikely, because of the large distance involved and because of the apparent lack of a plausible mechanism for such gradational differentiation.

Perhaps it is more likely that the Precambrian basement, whether of sedimentary or magmatic origin, became more magnetic as a result of an increase in temperature and metamorphic grade northeastward toward the more deeply buried Precambrian rocks, and toward the Uncompahgre Plateau and Rocky Mountains. A regional temperature increase is possible because the thermal gradients and heat flow in the adjoining Rocky Mountains are comparatively high (Birch, 1950). Dudarev (1960) found, from study of more than 10,000 rock samples, that their magnetic susceptibility was a function of depth, and presumably of temperature and pressure, which in turn affected the degree of metamorphism. Pavlides and Milton (in Pavlides, 1962, p. 96, 97, 100) found that magnetite in the metamorphosed shale and argillite of the Maple and Hovey Mountains area of Aroostook County, Maine, was formed by metamorphism, although it was generally restricted to structurally disturbed areas rather than being regionally distributed.

An increase in temperature of the more deeply buried basement to the northeast would also increase the magnetization by increasing the magnetic susceptibility and by changing the direction and intensity of remanent magnetization. Susceptibility of magnetite and other ferrimagnetic minerals increases with temperature until it reaches the Curie point, where it drops sharply to zero. According to Akimoto (1951), the average temperature coefficient of magnetic susceptibility of 15 titaniferous magnetite specimens is about 6.8×10^{-5} emu (electromagnetic units) per 1°C, and of pure magnetite about 7.2×10^{-5} emu per 1°C. On this basis, and if a basement rock containing 1 percent magnetite by volume is assumed, an unreasonably high temperature increase of about 250°C would be required to cause completely the gradational increase in magnetic intensity of about 100 gammas. This effect is therefore probably inadequate to entirely bring about the increase in magnetization.

The gradational increase in magnetic intensity may be attributed partly to the more rapid decay of thermoremanent magnetization where temperatures of the crystalline rocks are higher and to concurrent generation of viscous remanent magnetization (Doell and Cox, 1961, p. 234). The viscous remanent magnetization would be alined with the earth's field and would therefore reinforce the induced magnetization of the crystalline rocks.

No information is available on the direction or intensity of remanent magnetization of Precambrian basement rocks in the Moab-Needles area. Some information is available, however, from a core of Precambrian rock from a deep well in the Lisbon Valley area, about 40 miles southeast. This core, from the Pure Oil Co. NW. Lisbon-U.S.A. 2A well, east of the report area in sec. 10, T. 30 S., R. 24 E., San Juan County, Utah, was made available by W. F. Robertson, Jr., Area Geologist, Pure Oil Co. The core, which was obtained at a depth of 9,309–9,310 feet beneath the ground surface and 28–29 feet beneath the Precambrian surface, is an altered biotite-quartz monzonite. Its magnetic susceptibility is 1.45×10^{-3} emu and its thermoremanent magnetization 0.17×10^{-3}. The remanent magnetization was found to be nearly horizontal, or perpendicular to the vertical axis of the cylindrical core; but its direction with reference to north is not known (magnetic measurements by L. Allan White, U.S. Geol. Survey). Thermoremanent magnetization of the Precambrian basement rocks may be nearly horizontal in the Moab-Needles area as well as at Lisbon Valley. If so, observed magnetic intensities should increase in the northern part of the Moab-Needles area where higher temperatures of the more deeply buried basement rock would result in more rapid decay of thermoremanent magnetization and its replacement by viscous remanent magnetization.

In summary, at least part of the gradational northeastward increase in magnetic intensity may plausibly be attributed to a northeastward increase in basement temperature. This temperature increase would produce a gradational increase in susceptibility of the ferrimagnetic minerals of the basement, together with changes in thermo- and viscous-remanent magnetization that would reinforce the effect of increased susceptibility. Also contributing to the observed magnetic effects may be a northeastward increase in magnetic mineral content, resulting from gradational changes in the degree of metamorphism. An intrabasement mass of magnetic material at great depth cannot be excluded from the available data, though there is no discernible gravity evidence for such a mass and its existence is even more problematical than the postulated temperature effects.

Although the magnetic contours are generally parallel to the salt anticlines of Moab and Salt Valleys, in the extreme northeastern part of the area, there is no apparent magnetic expression of deep-seated structural displacements underlying the salt anticlines. According to gravity evidence (discussed on p. C16), the rocks below the salt are displaced downward to the northeast under Moab anticline, whereas the magnetic intensity increases to the northeast.

CENTRAL PART OF AREA

In the central part of the area three prominent magnetic highs at Upheaval Dome, Grays Pasture, and Hatch Point are associated with deep-seated masses of comparatively magnetic rock 5–7 miles in diameter. These magnetic masses are surrounded by rocks of lower magnetization than the basement rocks in the northern part of the area. The magnetic low northeast of the highs at Upheaval Dome and Grays Pasture is partly an associated polarization low. The polarization low north of the Hatch Point high is small owing to minor regional variations in magnetization of the Precambrian rocks; Precambrian rocks north of the Hatch

Point area are slightly more magnetic than those north of Upheaval Dome and Grays Pasture. A magnetic metagabbro pluton, 2 miles in diameter, was found by Case (1966) in the exposed Precambrian basement of the northwestern Uncompahgre uplift, in the lower canyon of the Little Dolores River. Similar mafic intrusions may occur in other parts of the region.

The form of the anomalies indicates that the magnetization is largely alined with the earth's present field, and that remanent magnetization is either comparatively weak or is almost parallel to the induced magnetization.

By use of the method of Vacquier, Steenland, Henderson, and Zietz (1951), the source of the Upheaval Dome anomaly has been estimated to be about at sea level, and that of the Grays Pasture anomaly about 1,000 feet below sea level (Joesting and Plouff, 1958, p. 89). The source of the Hatch Point anomaly is estimated to be 2,500–3,000 feet below sea level. These estimates are the elevations of the upper surfaces of the causative magnetic masses, which are assumed to be the Precambrian surface. The contrast in magnetic susceptibility, disregarding the remanent magnetization effect, is estimated to be 0.003–0.004 cgs units; thus the anomaly-producing rocks are considerably more magnetic than the surrounding rocks.

These estimates of depths and of contrasts in magnetic susceptibility were based on the assumption that the anomalies are caused by vertical prisms of uniformly magnetized rock of infinite downward extent. Depths to sources of the observed anomalies were estimated by comparing them with computed anomalies associated with appropriate prismatic models, magnetized in a field parallel to the earth's field. Accuracy of the depth estimates obviously depends on the appropriateness of the comparison as well as on the accuracy of the magnetic data. For example, a less than infinite vertical depth extent of the magnetic mass would yield too small a computed depth, although for practical purposes a depth extent equal to the depth of burial may be considered almost infinite. Nonvertical sides or nonuniform magnetization of the assumed prism would doubtless also cause errors in estimate depths. Our experience has been that depths to magnetic sources estimated according to the Vacquier method are often shallower than actual depths.

As an independent check on the depth estimates, just described, R. G. Henderson analyzed the Upheaval Dome anomaly by a new downward-continuation method that he derived (written commun., 1964). In this method magnetic anomalies are computed at successively lower levels closer to the apparent surface of the magnetic body to obtain a depth function. The depth function yielded an estimated depth of about 10,000 feet below the 8,500-foot aeromagnetic flight altitude, about 1,500 feet below sea level. This estimate agrees more closely with available subsurface evidence than did the earlier depth estimates.

In the Husky Oil Co. Buck Mesa 1 well, about 1 mile east of Upheaval Dome, Mississippian rocks were penetrated at 560 feet below sea level. Three miles farther southeast in the Pan American Petroleum Corp. Murphy Range 1 well Mississippian rocks were penetrated at 525 feet above sea level (fig. 2), and the McCracken Member of Knight and Cooper (1955) of the Upper Devonian Elbert Formation at 399 feet below sea level. Two miles still farther southeast in the Shell Oil Co. Murphy Range 1 well Mississippian rocks are 44 feet above sea level, or nearly 500 feet lower than in the Pan American well. On the basis of stratigraphic information extrapolated from the Midwest Exploration Co. Hughes 1 well on the Monument uplift, about 45 miles south of Upheaval Dome, and on isopach maps compiled by Cooper (1955), the Precambrian surface is estimated to be about 2,500 feet below sea level at the Husky Oil Co. Buck Mesa 1 well and about 1,500 feet below sea level at the Pan American Petroleum Corp. Murphy Range 1 well.

It is difficult to judge the accuracy of these estimates, owing to probable structural complexities and uncertainty of the thickness of pre-Upper Devonian sedimentary rocks. Apparently, though, the Precambrian surface rises rather sharply southwestward to the vicinity of the Pan American Petroleum Corp. Murphy Range 1 well, and then falls away sharply for at least a short distance before again rising southwestward to the Monument uplift. The scanty evidence precludes determination of whether the Upheaval Dome and Grays Pasture anomalies in part represent anomalous topographic highs on the Precambrian surface. The anomalies represent compositionally distinct and more magnetic parts of the Precambrian rocks that may coincide with structural boundaries. Their depths are almost certainly greater than estimates based on the Vacquier method. At Upheaval Dome, depth estimates based on the downward-continuation method and stratigraphic extrapolation are believed to be more accurate.

At the Grays Pasture magnetic high the Precambrian surface is about 2,500 feet below sea level, according to computations based on R. G. Henderson's downward-continuation method (written commun., 1964). This result is more in accord with available stratigraphic and structural information, as well as with the magnetic gradients; it is therefore assumed to be more accurate than estimates based on the method of Vacquier, Steenland, Henderson, and Zietz (1951).

The prominent magnetic highs at Upheaval Dome, Grays Pasture, and Hatch Point may be associated either with comparatively magnetic Precambrian rocks—at anomalously shallow depths because of structural disturbances—or with younger igneous intrusions that extend above the Precambrian surface. Precambrian mafic rocks, such as gabbro, at the site of structural uplifts of the Precambrian basement would seem to be a more likely explanation, as no post-Precambrian igneous rocks are known in the area. There is no surface structural expression of such an uplift; hence the uplift would necessarily be older than the Pennsylvanian upper part of the Hermosa Formation, the oldest formation exposed in the immediate locality.

Because of a 10-gamma residual anomaly found in several airborne magnetic profiles flown at 7,500 feet above sea level over the structure, it was considered necessary to postulate in an earlier paper (Joesting and Plouff, 1958, p. 91–92) that Upheaval Dome was the locus of a small shallow igneous intrusion. It was recognized, however, that a salt plug was probably the major cause of the dome. Ground magnetic surveys were later made in Upheaval Canyon and in the crater of Upheaval Dome to check the existence of the indicated anomaly of shallow origin and to relate its location closely to points on the surface. No shallow-source anomaly was detected by the ground survey, which was made at altitudes several thousand feet below the aeromagnetic survey. We therefore concluded that there is no magnetic evidence for a small igneous intrusion.

Upheaval Dome and its associated rim syncline (frontispiece; pl. 1) were considered by McKnight (1940, p. 124–128) to have probably been formed by salt squeezed up from the underlying Paradox (salt) Member but not yet exposed by erosion. The rim syncline resulted from plastic flow of salt from the salt formation into the dome under differential gravitational stress. McKnight's conclusions were based on knowledge of a thick salt section at moderate depth, the symmetrical, nearly circular dome and rim syncline, and the apparently slow rate of deformation. These conclusions favoring a salt-intrusion origin of Upheaval Dome are in agreement with theoretical and experimental studies of the mechanics of salt dome formation by Nettleton (1934) and Parker and McDowell (1955).

Marked thinning of the Upper Triassic Wingate Sandstone, wherever it has been observed along the axis of the rim syncline, is a puzzling feature of the dome. Normal thickness of the Wingate in adjoining undisturbed areas is about 300 feet; its thickness on the east side of the rim syncline is 30–40 feet (McKnight, 1940, p. 125–126), and on the south side, about 100 feet. The overlying Kayenta Formation of Late Triassic(?) age is also thinner in the disturbed area. It is 210 feet thick in one locality (Fiero, 1958), or 50 feet less than the normal thickness outside the structurally disturbed area.

McKnight concluded tentatively that thinning of the Wingate at the axis of the rim syncline resulted partly from horizontal faults that he did not observe in the short time available for his examination. The beds, however, are not conspicuously shattered. Fiero (1958) believed that the Wingate and the overlying Kayenta Formation had a high water content before consolidation and were stretched and thinned plastically in the trough of the syncline. Whatever the mechanism, thinning of the beds before consolidation appears to be more likely in consideration of the apparent absence of horizontal faults. The increased dip of bedding planes in the Wingate Sandstone on the south side of the structure toward the axis of the syncline supports this explanation. The increased dip is generally coincident with thinning of the sandstone, which rests on the underlying formation with no apparent discordance. In addition to probable deformation of Upheaval Dome during Late Triassic time, renewed doming and synclinal subsidence took place during Jurassic time or later, as shown by the folded Jurassic rocks exposed in the rim syncline.

A cryptovolcanic origin for Upheaval Dome was advocated by Bucher (1936) because of the dome's similarity to probable cryptovolcanic structures in other regions, including regions where no deposits of salt or gypsum are known in the underlying formations. Many of these structures have associated peripheral synclines, and all have intensely deformed and shattered domal structures. Some of them evidently formed in a short interval of time.

We agree with McKnight and Fiero that Upheaval Dome probably resulted from plastic flow and intrusion of salt into the overlying beds. The long-continued and repeated deformation of the structure suggests intrusion of salt rather than of igneous rock as a cause. In addition, absence of a magnetic anomaly that might be associated with a near-surface igneous intrusion is considered to be unfavorable to an igneous or cryptovolcanic origin. Evidence based on the gravity survey will be discussed later (p. C17).

Upheaval Dome structure is much too small to be a major or direct source of the broad magnetic high that is centered over the structure. The rim syncline is only 2 miles in diameter, whereas the source of the well-defined magnetic high is more than 5 miles in diameter. The indicated basement structural feature along the northeast flank of the magnetic high may have controlled the position of the salt dome that evidently formed Upheaval Dome, especially if the rocks below the salt were displaced while the evaporites were being deposited, or while they underwent plastic flow and migration. It is not clear, if the basement structural control exists, why salt domes are not also at Grays Pasture and Hatch Point, where similar basement structures are indicated by magnetic and gravity anomalies.

SOUTHERN PART OF AREA

The prominent rounded magnetic anomalies in the southern third of the area are associated with the Precambrian rocks of the northern end of the north-plunging Monument uplift. As already indicated (p. C7), removal of the prominent highs and lows leaves a regional magnetic field having about the same intensity as the regional field in the remainder of the Moab-Needles area. This rather uniform field may indicate that the Precambrian rocks were originally of comparatively uniform magnetization and composition. The local anomalies, then, may have resulted from intrusion of more highly magnetic (and generally denser) rocks into an originally uniform basement. Such intrusions presumably occurred during the Precambrian, as they have no apparent local structural effect on the overlying Paleozoic rocks.

A diverse magnetic pattern similar to that over the Monument uplift was observed over the Uncompahgre uplift to the east (Joesting and Byerly, 1958, p. 8–9; Joesting and Case, 1962, p. 1882) and over the San Rafael Swell to the west. This diverse pattern appears to be characteristic of the structurally uplifted regions of the Colorado Plateau, in contrast with the comparatively uniform magnetic pattern characteristic of the adjoining deeper basins to the north and east.

In the southern part of the Moab-Needles area the Precambrian surface is about a mile closer to the aeromagnetic flight level than in the deep basin to the north; hence the amplitudes and gradients of the anomalies are correspondingly higher in the southern part of the area. To compare the configurations of the magnetic fields associated with uplift and basin on the same datum, the field over the uplift was computed upward 1 and 2 miles above the observational datum (Henderson, 1960). Amplitudes and gradients of the rounded anomalies were decreased considerably, but the distinctive pattern remained. Similarly, the prominent highs at Upheaval Dome and Grays Pasture retained their characteristic rounded forms when calculated for higher altitudes. The amplitude of the Upheaval Dome anomaly decreased from about 400 gammas at flight level (8,500 ft above sea level) to about 225 gammas 1 mile above flight level and about 175 gammas 1½ miles above flight level. These computations demonstrate that the comparatively magnetic rocks which produce the rounded anomalies in the uplifted areas are not present in the basin to the north.

Differences in magnetic pattern of uplift and basin indicate differences in composition of the underlying Precambrian rocks that have existed since Precambrian time. These differences are therefore considered evidence of ancestral Precambrian counterparts of the present uplifts and deeper basins of the Colorado Plateau. According to this view, the present structural features are rejuvenations of the older ones, along nearly the same structural boundaries.

INTERPRETATION OF THE GRAVITY ANOMALY MAP

In its regional aspects the gravity anomaly map to a large extent reflects density contrasts within the Precambrian basement, just as the magnetic map reflects magnetization contrasts. The two maps are therefore in part complementary, although the gravity map is also affected markedly by density contrasts in the overlying clastic sedimentary rocks and between these rocks and the evaporites.

The gravity contours indicate a broad regional northward decrease in gravity values, from a high of 134 mgal south of The Needles to a low of about 90 mgal north of Bartlett Flat (pl. 4). This strong regional gradient reflects contrasts in density and composition within the Precambrian basement; the basement rocks to the south are denser than those to the north. The gradient also reflects both increasing depth of the relatively dense Precambrian basement toward the northeast and depositional thickening of the evaporite beds of the low-density Paradox toward the northeast.

Prominent gravity lows, superimposed on the regional pattern, occur over the Moab Valley and Salt Valley salt anticlines; these lows are clearly related to the thickened salt cores of the anticlines. The most prominent anomaly, however, is a zone of steepened gravity gradient that trends slightly north of west across the area from Kane Springs Canyon, between Grays Pasture and Big Flat, to the Green River, between Upheaval Dome and Mineral Point. This steep gradient probably marks the site of a deep-seated structure that divides the buried Paradox basin into a southern shallow part and a northern deep part. Across this zone the Paradox evaporites thicken toward the northeast. A pre-Paradox warp, or zone of distributive faults, downthrown to the north, may control the thickening of the evaporites. Moreover, both the density and magnetization of the Precambrian rocks and hence their composition differ markedly across the zone.

Elsewhere, in similarity with the magnetic contours, gravity contours show generally broad highs and lows which have little correlation with surface structural features. Some of the gravity anomalies coincide with equivalent magnetic anomalies; this coincidence indicates common Precambrian sources. Others, however, do not correlate particularly well with magnetic anomalies and thus indicate that some gravity anomalies originate within the overlying sedimentary rocks.

REGIONAL GRAVITY GRADIENT FROM UPHEAVAL DOME AND GRAYS PASTURE TO BIG FLAT

The zone of steepened gravity gradient from Kane Springs Canyon to the Green River, between Grays Pasture and Upheaval Dome on the south, and Big Flat and Mineral Point on the north, results mainly from contrasts in density within Precambrian rocks. Evidence for this is summarized in the discussion that follows:

Well data along profile *A–A′* are shown in figure 3*A*. Control is moderately good near both ends of the profile, where several wells bottomed in Mississippian or older rocks. These wells indicate that considerable relief exists on the surface of the Mississippian rocks. A conspicuous structural high is southeast of Upheaval Dome at the Pan American Petroleum Corp. Murphy Range 1 well, where Mississippian rocks were found at +518 (sea-level datum) and Devonian rocks at −74 feet. In the Shell Oil Co. Murphy Range 1 well, 2 miles to the southeast, Mississippian beds were penetrated at +44 feet, and Devonian beds at −518 feet. In the Husky Oil Co. Buck Mesa 1 well, 3 miles northwest of the Pan American well and near Upheaval Dome, Mississippian beds were penetrated at −560 feet; the well was bottomed in Mississippian beds at −888 feet. The basement surface is assumed to be approximately conformable with the structural high indicated by Mississippian tops, although additional complexity would doubtless be revealed by additional deep drilling.

The salt beds of the Paradox, which are only about 1,000 feet thick in the indicated structural high near the Pan American well, thicken to an estimated 1,600 feet at the Shell Oil Co. Murphy Range 1 well, 2 miles to the southeast, and to 1,467 feet at the Husky Oil Co. Buck Mesa 1 well, 3 miles to the northwest.

From the Buck Mesa well northeastward, the salt thickens to nearly 3,000 feet at the British-American Oil Producing Co. Federal-Ormsby 1 well and to 3,500 feet at the Glen Ruby Unit 1 well at Big Flat. The base of the salt drops from about 800 feet above sea level, at its highest known position at the Pan American Petroleum Corp. Murphy Range 1 well, to 1,600 feet below sea level at the Federal-Ormsby 1 well. It then rises across the dome at Big Flat to about 1,300 feet below sea level at the Pure Oil Co. Big Flat 1 well and finally drops off from Big Flat to about 5,000 feet below sea level at Moab anticline (Hite, 1960, fig. 1). Mississippian beds are concordant with the base of the salt, as far as can be determined from the well data.

The gravity data are shown in figure 3*B*. The computed gravitational effects of northward salt thickening and increasing depth of Mississippian rocks amount to only 6–8 mgal along profile *A–A′*. Data from deep drill holes just north and northwest of the Moab-Needles area indicate that northward thickening of the pre-Paradox Paleozoic beds and of the salt is insignificant and can cause only a few milligals of the observed anomaly of 40 mgal. Most of the 40-mgal decrease in gravity values along *A–A′* must therefore be attributed to lower density basement rocks to the north.

For figure 3*C* a model has been assumed whose gravitational effects approximate the observed gravity anomaly along profile *A–A′*. Salt thickening is assumed to increase gradually northward, and a major density contrast in the Precambrian basement is assumed. In the calculations, a density of 2.6 g per cm^3 was assigned to beds just above the salt, 2.65 g per cm^3 to Paleozoic beds below the salt, 3.0 g per cm^3 to dense Precambrian rocks to the south, and 2.7 g per cm^3 to Precambrian rocks of lower density to the north. These values are only approximations, but they yield reasonable density contrasts that could give rise to the observed gravity anomaly.

The inclination and location of the deep-seated contact between Precambrian units shown in figure 3*C* are, of course, schematic. Moreover, the gravitational effects of the model do not completely reproduce the total anomaly of 40 mgal; hence density contrasts within the Precambrian basement are greater than 0.3 g per cm^3, or the thickness of the zone of Precambrian density contrasts is greater than the 10,000-foot thickness assumed in the model. If the model is approximately correct, then Upheaval Dome lies just southwest of a deep-seated fault zone or a deep-seated hinge line.

Contours defining the Grays Pasture–Big Flat regional gradient are split by a nosing at Hatch Point and Bridger Jack Mesa. The main part of the zone of steepened gradient continues eastward into the La Sal Mountains regional gradient where it, or an equivalent zone, changes strike abruptly to the northeast, along the northwest flank of the La Sal Mountains (Case and others, 1963, pl. 17). The southern segment of the zone trends southeast along Hatch Point and Harts Point. It may represent a zone of density contrasts within the Precambrian basement, but it more probably is related to salt thickening and increasing basement depth toward Lisbon Valley.

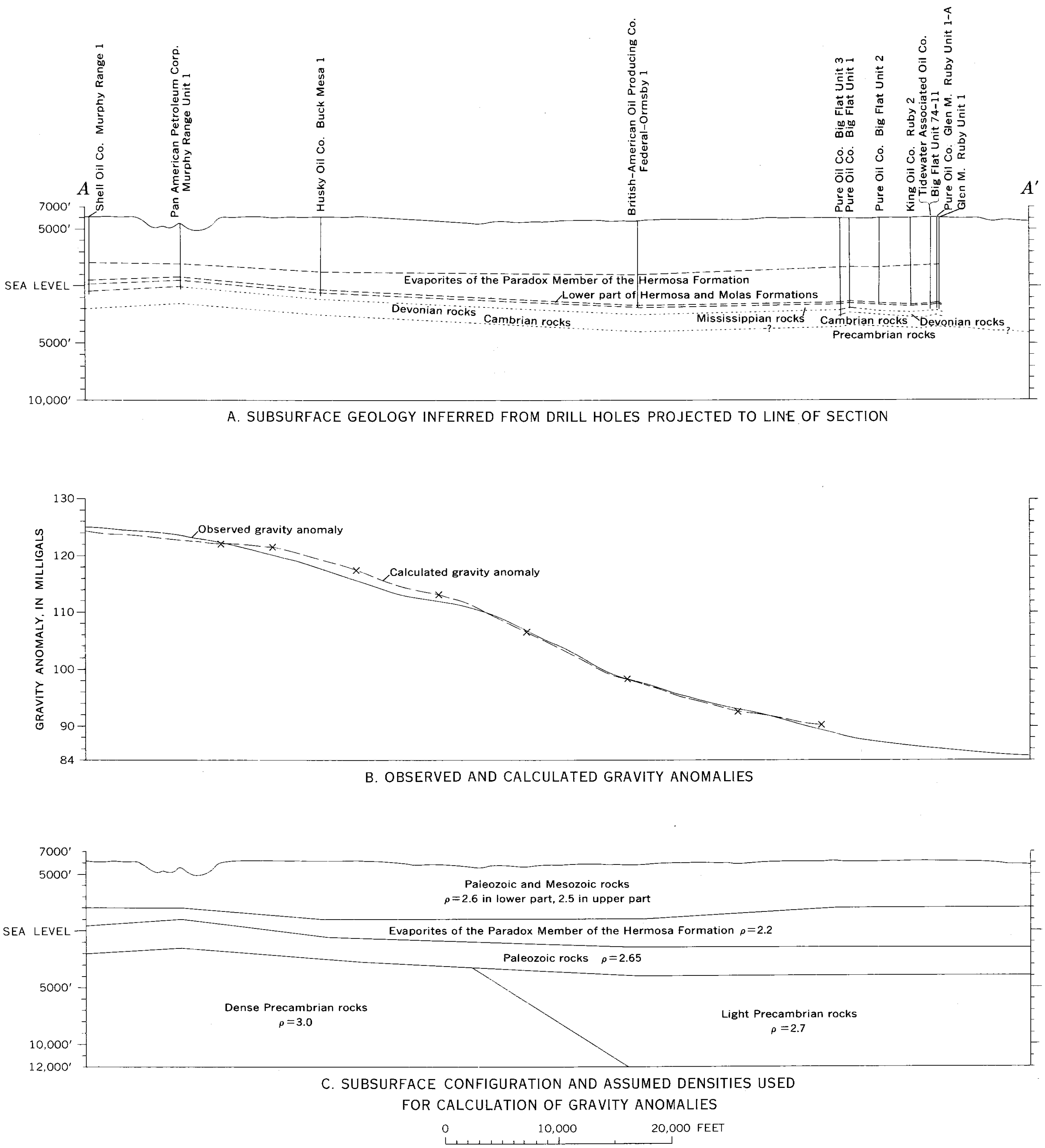

FIGURE 3.—Geologic and gravity profiles across the Grays Pasture–Big Flat area. Line of section *A–A′* shown on generalized geologic map.

OTHER REGIONAL GRAVITY ANOMALIES

The 4- to 6-mgal gravity highs just south of Upheaval Dome and Grays Pasture apparently reflect in part a structural high or highs in the comparatively dense rocks below the salt, and correspondingly thinner salt, as indicated by drilling. These local structural features are the causes for the lack of complete coincidence of gravity highs with the magnetic highs at Upheaval Dome and Grays Pasture, although the magnetic and gravity anomalies are largely related to the same dense and magnetic Precambrian source. The gravity high at Bridger Jack Mesa and Kane Springs Canyon is located near the third large magnetic high in the central part of the area. Again, relatively dense and magnetic rocks are responsible for the highs. The similarity of amplitude and shape of the three magnetic anomalies and their coincidence with gravity highs indicate that all three anomalies are caused by the same type of Precambrian rock, perhaps a mafic or ultramafic intrusive rock.

The small gravity lows at the Green River 6 miles south of Holeman Spring Basin and just south of the Shell Oil Co. Murphy Range 1 well are probably related to salt thickening and to greater depth to presalt rocks, as suggested by drill data. They may also be related to less dense basement, in line with magnetic evidence of a contact between magnetic and comparatively nonmagnetic basement rocks, southwest of the Upheaval Dome and Grays Pasture highs.

Farther south, a broad circular gravity low is located over the northern part of The Needles region. This low is probably related to thicker salt and to greater basement depth, as suggested by the few drill data, but it may also reflect lower density of the basement.

The gravity high near Beef Basin at the northern nose of the Monument uplift is related mainly to structural uplift, and in part to thinning of salt. Another high at the Wayne-Garfield County line, west of the Colorado River, may be related to a deep-seated northwest continuation of the Monument uplift that is not reflected in the surficial structure.

In the northern part of the area, a positive nose in the gravity contours northwest of Bartlett Flat approximately coincides with northeastward-trending magnetic contours. These anomalies are almost certainly caused by deep-seated intrabasement contrasts rather than by structural relief of the basement, as they trend at right angles to structure contours on top of the Mississippian (fig. 2).

GRAVITY ANOMALIES RELATED TO SALT ANTICLINES

SALT VALLEY ANTICLINE

A 26-mgal low occurs over Salt Valley anticline in the extreme northeastern part of the area. The amplitude of the salt core of the anticline was computed as about 8,000 feet (Joesting and Case, 1962, p. 1887–1888). The gravity low continues southeastward toward Fisher Valley salt anticline, which is part of the same anticlinal system (Case and others, 1963, p. 107).

MOAB VALLEY ANTICLINE

A residual gravity low associated with the Moab Valley salt anticline is 20–22 mgal. The low is centered near the city of Moab, just south of the Colorado River, and continues southeastward into Spanish Valley in the La Sal Mountains area (Case and others, 1963, p. 108). To the northwest, beyond the area of this report in the Salt Valley–Cisco area, a small gravity low at Tenmile Wash is on the same trend as Moab anticline and is probably related to a small deep-seated salt core that is part of the Moab anticlinal system (Joesting and Case, 1962, p. 1888). The rather steep regional gravity gradient across Moab Valley indicates that the Precambrian basement is deeper—and possibly less dense—beneath and northeast of Moab Valley than it is to the southwest. The greater depth is confirmed by the available well data.

Northwest of Moab, the Delhi Oil Co. Utah 2 well (sec. 18, T. 25 S., R. 21 E.) went through more than 7,000 feet of evaporites and related rocks and was bottomed in the lower member of the Hermosa Formation or in Mississippian strata at 5,086 feet below sea level (Hite, 1960, fig. 1). South of Moab Valley the Humble Oil and Refining Co. Bridger 1 well (sec. 17, T. 27 S., R. 22 E.) penetrated Mississippian rocks at 1,670 feet below sea level and Cambrian rocks at 2,520 feet below sea level. Structural relief on the Mississippian between the two wells is therefore about 3,400 feet.

Depth to Mississippian rocks increases to the north and northeast of Moab Valley. The Richfield Oil Corp. Onion Creek well (sec. 31, T. 23 S., R. 24 E.), 15 miles northeast of Moab, bottomed in Paradox evaporites at 9,615 feet below sea level. The Pacific Equity Oil Co. Thompson well, north of the mapped area (sec. 33, T. 21 S., R. 21 E.), bottomed in Paradox evaporites at about 8,700 feet below sea level (Herman and Sharps, 1956, fig. 4).

Thus increasing depths of Mississippian strata, depositional thickening of the Paradox evaporites, and probable decreasing basement density toward the northeast together account for the regional gravity gradient across Moab Valley (fig. 4*A*).

Inasmuch as the gravity low over Moab Valley is centered southeast of the Delhi well, the salt is probably thicker or the basement is deeper near Moab than near the well.

Inferred deep-seated relations from Cane Creek anticline to the region northeast of Moab anticline are shown in figure 4*B*. Note that the total thickness of salt at Cane Creek anticline is about 5,000 feet, on the basis of well data. Increasing depth, to the northeast, of rocks below the salt is indicated schematically, as guided by regional subsurface data, although no deep wells penetrate the total column of salt along the line of profile northeast of Cane Creek anticline. Absence of the salt on the southwest flank of the Moab anticline is assumed from analogy with other anticlines of the region. The existence of the abrupt warp or scarp rocks below the salt, shown at the southwestern margin of the Moab anticline, is inferred primarily on analogy with relations along other salt anticlines of the region, notably Paradox Valley and Lisbon Valley anticlines.

If a linear regional gravity gradient is assumed across Moab Valley, the residual anomaly over the anticline is about −22 mgal. A simplified model of the anticline is shown in figure 4*C*. The calculated gravitational effects of the model approximately reproduce the residual anomaly. In the calculations the following assumptions were made: The density contrast between the evaporites in the core of the anticline and the exterior sedimentary rocks is about 0.35 g per cm^3 and the amplitude of the salt core is about 8,000 feet.

A better fit of the calculated and residual anomalies could be obtained by changing the inclination of the assumed regional gradient, by changing the density contrasts, or by changing the thickness of the anomalous salt mass. In consideration of the many uncertainties, however, an exact match of the curves is not warranted. A density contrast of 0.35 g per cm^3 is believed to be a reasonable value. Such a contrast would exist if the salt density were 2.2 g per cm^3 and the average density of the adjacent sandstone, shale, and limestone were 2.55 g per cm^3.

CANE CREEK ANTICLINE

The strong regional gravity gradient at Cane Creek anticline and wide spacing of gravity stations evidently combined to obscure any associated local closed gravity anomaly. The slight flattening of the gradient across the anticline may be related to salt thickening. The apparent asymmetry of the anticline is perhaps another reason for lack of an observed anomaly: structural relief on the southwestern flank of the anticline is only 500 feet and, if this is the extent of salt thickening, it would give rise to an anomaly of only about 2 mgal. Relief on the northeastern flank is apparently greater, but nothing is known about how this relief is absorbed between Cane Creek anticline and Moab anticline. Finally, terrain corrections are relatively large and elevation control is poor in the vicinity of Cane Creek anticline, so that the data may not be sufficiently precise to show the gravity effects of the salt anticline.

UPHEAVAL DOME

The nature and amplitude of the exact residual gravity anomaly over Upheaval Dome are virtually impossible to isolate as they are obscured by regional gravitational effects and local terrain effects. Terrain corrections were as large as 8 mgals in and near the crater of the dome. Apparently a small residual high of about 2–3 mgals occurs over the dome. A low of 1 mgal, centered on the vertical axis of the dome, is superimposed on the gravity high. If the dome is presumed to be represented at depth by a vertical cylinder of salt, whose length is 3,000 feet and whose radius is 2,500 feet, and the density of the salt is assumed to be 0.3 g per cm^3 less than that of the enclosing rocks, the theoretical gravity anomaly at a point on the axis of the cylinder, 1,000 feet above its top, is about −3.7 mgals. The small residual high could be caused by dense rocks in the basement or by upward tilting of upper limestone of the Hermosa around the periphery of the dome. Nevertheless, the small low centered at the crest of the dome indicates that the dome probably has a salt core.

SPANISH BOTTOM

A detailed survey of a small area was made over the evaporites exposed in a dome at Spanish Bottom, near the head of Cataract Canyon. A low gravity flexure of about 2 mgals was detected over the dome, but its minimum is east of the center of the dome. Terrain corrections are so much larger than the amplitude of the anomaly in the floor of the canyon that quantitative interpretations of the anomaly are not warranted.

CONCLUSIONS

The buried Precambrian basement in the northern part of the Moab-Needles area is magnetically rather uniform; such uniformity appears to be characteristic of the basement in the deeper parts of the Paradox salt basin. The Precambrian basement in the southern part of the area is magnetically diverse; this diversity is apparently characteristic of the basement in many of the exposed and buried uplifts bordering the salt basin.

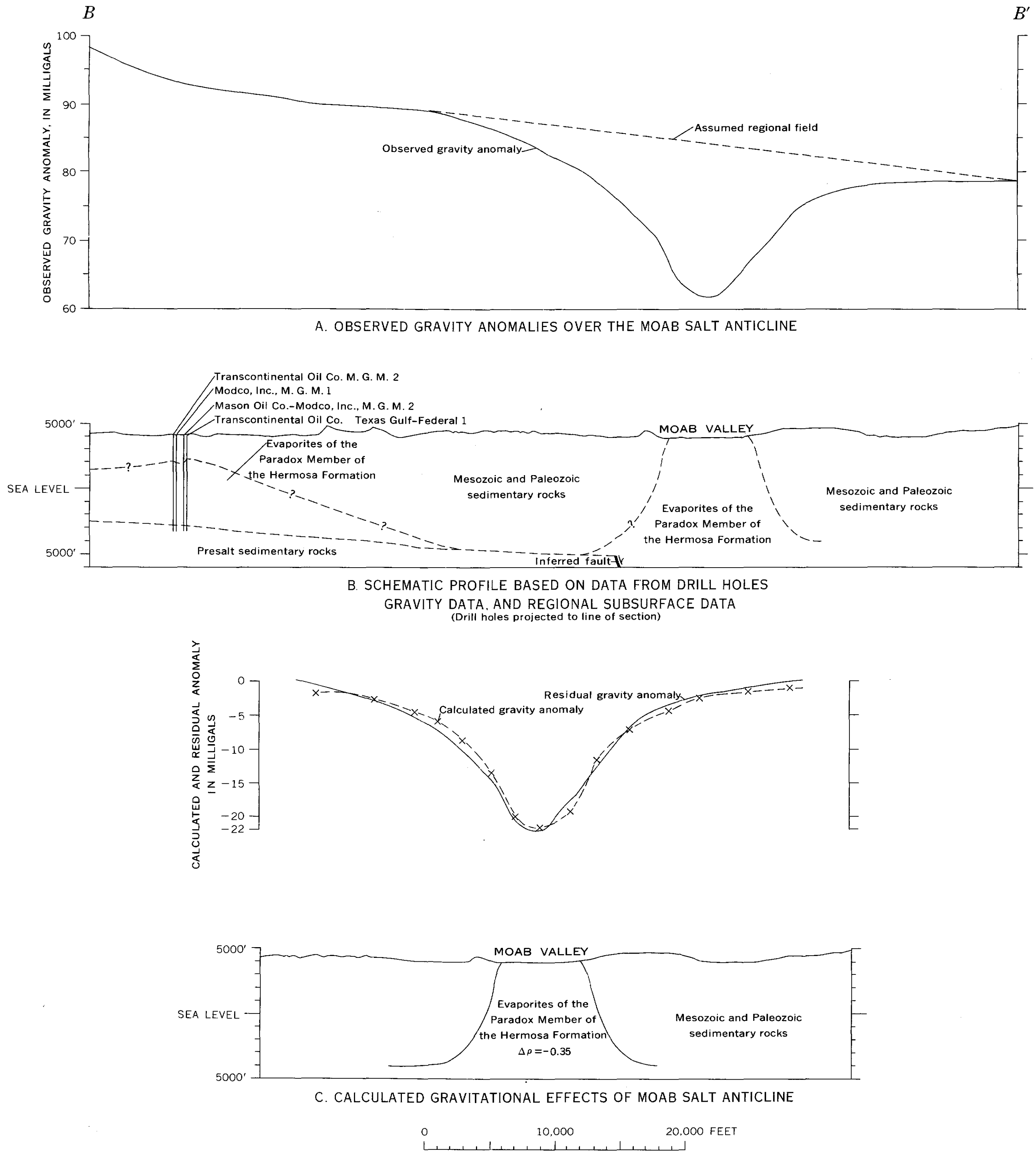

FIGURE 4.—Geologic and gravity profiles across Cane Creek anticline and Moab anticline. Line of section, *B–B′*, shown on generalized geologic map.

Generally, the magnetic field associated with the basin increases gradationally northeastward, toward its deepest part. Possible causes are: (1) A gradational northeastward increase in ferrimagnetic mineral content of the Precambrian basement, because of gradational variation in original composition or change in metamorphic grade; (2) increase in temperature; or (3) an intrabasement mass of magnetic material.

Magnetic and gravity trends are predominantly northwestward, in line with the main regional structural trends and axes of the salt anticlines. A deep-seated northeast-striking regional structural trend with apparent left-lateral displacement is indicated by well-defined magnetic and gravity trends that extend beyond the Moab-Needles area. This indicated transverse structure coincides with the generally straight course of the Colorado River, although surface rocks are not displaced, insofar as is known. Deep drilling partly confirms the presence of an asymmetric structural trough alined with the Colorado River.

Upheaval Dome is probably caused by a salt plug that did not reach the present surface. A large magnetic anomaly centered at Upheaval Dome is related to an underlying Precambrian basement intrusion, rather than to the structural dome itself. However, this anomaly and associated anomalies mark the approximate position of a buried structural zone separating the deeper part of the basin to the north from the shallower part to the south; the structural zone may have controlled the position of the salt plug. Two similar prominent magnetic anomalies with no surface structural expression were observed in the eastern part of the area along the deep-seated structural zone.

Gravity values are generally lower in the northern and eastern parts of the area, in keeping with the greater depth to the Precambrian surface and the thicker evaporites. However, analysis of the steepened gravity gradient extending westward from Bridger Jack Mesa across Grays Pasture and Buck Mesa to the Green River indicates that only a small part of the southward increase in gravity values can be attributed to salt thinning and to relief on the Precambrian surface. Most of the gradient is caused by density contrasts within the Precambrian rocks; these rocks are denser south of the zone of steepened gradient than to the north. Gravity highs at Holeman Springs Basin, in the area south of Grays Pasture, and at the head of Kane Springs Canyon are related to structurally high relatively dense magnetic rocks and coincide with magnetic highs already discussed.

A gravity high east of Beef Basin at the south boundary of the area reflects the structural high at the north end of the Monument uplift. A broad low just to the north, near The Needles, and other small-amplitude anomalies may result from lower density, deeper basement, or from thicker salt.

Prominent gravity lows of 20 mgal and more are associated with the salt anticlines of Salt Valley and Moab Valley. Analysis of the residual low at Moab Valley indicates that the salt core rises about 8,000 feet above the top of the salt on either side. According to gravity evidence, Moab Valley salt anticline is controlled by a deep-seated fault, but there is no magnetic evidence of such structural control.

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