Regional Geophysical Investigations in the Central Colorado Plateau

GEOLOGICAL SURVEY PROFESSIONAL PAPER 736

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By J. E. CASE *and* H. R. JOESTING

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Gravity and magnetic anomalies indicate polygonization of the Precambrian basement complex and partial rejuvenation of basement structures during late Paleozoic and Laramide time

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REGIONAL GEOPHYSICAL INVESTIGATIONS IN THE CENTRAL COLORADO PLATEAU

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

ABSTRACT

Gravity and aeromagnetic surveys covering about 15,000 square miles in the central Colorado Plateau in Utah, Colorado, Arizona, and New Mexico were conducted to assist in determining the regional subsurface geology as it may relate to uranium, oil, and potash exploration.

Precambrian rocks, either exposed on the Uncompahgre Plateau or penetrated by drill holes, are granitic, dioritic, and gabbroic bodies and complexly folded gneisses and schists. The densities of these rocks range from about 2.6 to 3.0 grams per cubic centimeter, and their magnetic susceptibilities are as much as 5×10^{-3} electromagnetic unit.

Paleozoic sedimentary rocks attain a maximum thickness of about 17,000–18,000 feet in the deepest part of the Paradox basin, a concealed structural feature of late Paleozoic age. Cambrian, Devonian, and Mississippian rocks consist of limestone, sandstone, shale, and dolomite. Pennsylvanian rocks consist of limestone, sandstone, shale, and, in the Paradox Member of the Hermosa Formation, evaporites. Permian rocks include sandstone, arkose, limestone, and siltstone. The limestones and sandstones of low porosity probably have an average density close to that of parts of the Precambrian basement, 2.6–2.7 grams per cubic centimeter. The evaporites are of low density, 2.2–2.35 grams per cubic centimeter.

Mesozoic sedimentary rocks are dominantly clastic and attain a maximum thickness of about 5,000 feet. They are less indurated than the Paleozoic rocks, and their densities probably range from 2.3 to 2.5 grams per cubic centimeter.

Thin Tertiary and Quaternary deposits, which consist of alluvium and glacial deposits, locally cover large areas, but they have little influence on the geophysical anomalies.

Laccolithic intrusions of latest Cretaceous or Tertiary age form such prominent mountain groups as the Henry, La Sal, Abajo, and Carrizo Mountains, and the Sleeping Ute Mountain. These igneous masses consist of one or more central stocks from which radiate laccoliths, dikes, sills, and bysmaliths. They are composed of closely allied rocks which range in composition from microgabbro to granite, but which are predominantly diorite or monzonite porphyry. Their average densities are about 2.62 grams per cubic centimeter, and their average susceptibilities are about 0.002 electromagnetic unit. Small mafic dikes, plugs, and necks are distributed sporadically through the region, but these bodies are so small that they have little influence on the regional geophysical anomalies.

Regional geologic structures may be broadly grouped, according to age, as (1) those formed in the Precambrian; (2) those formed during late Paleozoic deformation of the region, including the Paradox basin, the ancestral Uncompahgre highland, and the salt anticlines; and (3) those formed during the Laramide, including the Uncompahgre uplift, San Rafael Swell, Monument uplift, Defiance (De-Chelly) uplift, and reactivated salt anticlines. Some of these later structures were probably rejuvenated along lines of weakness that were established during Precambrian and (or) Paleozoic times.

The gravity anomaly map shows several different types of anomalies. The dominant anomalies are conspicuous gravity lows over the salt anticlines. Both broad regional highs, which occur over the monoclinal uplifts where denser rocks are close to the surface, and regional lows, which occur over the basin and platform areas, are caused by lateral density contrasts related to structural relief. Superimposed on these broad anomalies are conspicuous highs and lows that are caused by rocks of different density within the Precambrian basement, by concealed major Paleozoic structures, and by variations in thickness of Paleozoic sedimentary rocks. Small gravity highs are located over most of the laccolithic mountains.

On the basis of analysis of combined drill data and gravity anomaly data, the amplitudes, or structural relief, of the salt cores of the anticlines were determined as follows: Salt Valley, 8,000 feet; Fisher Valley, 10,000 feet; Sinbad Valley, 9,000–11,000 feet; Castle Valley, 7,000 feet; Paradox Valley, 10,000 feet; Tenmile Wash salt anticline, 3,500 feet; Moab Valley–Spanish Valley, 8,000 feet; Pine Ridge, 4,000 feet; Gypsum Valley, 9,000–10,000 feet; Cane Creek anticline, 1,500–3,000 feet; Lisbon Valley, 4,500–8,000 feet; and Dolores anticline, 1,000–5,000 feet. Combined drill and gravity data indicate that grabenlike depressions underlie the salt at Paradox Valley, Moab Valley–Spanish Valley, and Lisbon Valley salt anticlines.

Most of the magnetic anomalies arise from contrasts in magnetization of the Precambrian basement. The deeper part of the Paradox basin is generally characterized by nearly flat magnetic gradients, which indicate the greater depth to the Precambrian surface. However, the flat or gentle magnetic gradients indicate, in part, that the basement is relatively nonmagnetic with respect to adjacent areas; thus, the deepest part of the basin is postulated to be underlain by a thick sequence of weakly metamorphosed or unmetamorphosed Precambrian sedimentary rocks.

Prominent magnetic highs are located over each of the main laccolithic groups at the La Sal, Abajo, and Henry Mountains, and the Sleeping Ute Mountain. A few positive anomalies near the exposed porphyry bodies of the mountain groups suggest shallow, but concealed, intrusions.

Analysis of combined magnetic, gravity, and well data indicates that the Precambrian basement is exceedingly

[1]Deceased, May 1965.

heterogeneous. From the anomalies one can define areas of Precambrian basement that are (1) dense and strongly magnetic, (2) of high density and moderate magnetization, (3) of intermediate density and moderate magnetization, (4) of low density and strong magnetization, (5) of intermediate density and weak magnetization, and (6) of low density and weak magnetization. When the areas of these anomaly types are plotted, a general polygonal basement pattern is evident. The trends of the major contacts or structural boundaries tend to fall into four rather distinct groups: northwest, northeast, east, and north. The conspicuous northeast lineaments are on trend, or en echelon, with shear zones that control the Colorado mineral belt and are part of a larger regional Precambrian structural zone that extends from the Grand Canyon area, Arizona, through the Rocky Mountains of northern Colorado and southern Wyoming, and into the High Plains of Wyoming. East-trending magnetic lineaments are conspicuous near the San Rafael Desert and San Rafael Swell. These, too, are part of a system of lineaments that extends from California to the High Plains of Colorado.

Some of these Precambrian lines of weakness were rejuvenated during the late Paleozoic — for example, the northwest-trending Uncompahgre front and the deep-seated faults associated with the salt anticlines in the Paradox basin. Some of the northeast-trending zones apparently were rejuvenated during the Paleozoic, as revealed by isopach maps of Paleozoic units. During the Laramide, northwest-trending zones were rejuvenated along the Uncompahgre front; north-trending zones along Comb Ridge monocline and Reef monocline; and northeast-trending zones along Comb Ridge monocline, Reef monocline, and elsewhere.

Major geologic features of potential economic significance that remain to be confirmed by drill holes include the postulated salt anticline at Tenmile Wash and the inferred deep-seated northeast-trending structural zone along the west flank of the La Sal Mountains. Both are potential oil traps, and the Tenmile Wash anticline may lie near the high-potash facies of the Paradox basin.

INTRODUCTION

During the years 1953–58 regional gravity and aeromagnetic surveys were conducted over about 15,000 square miles in the central Colorado Plateau by the U.S. Geological Survey in connection with the program of investigations of the geology over the region of major uranium deposits (fig. 1). The surveys were made to provide information on concealed and deep-seated structures that may have influenced the accumulation or distribution of uranium deposits and on other aspects of the regional geology not obtainable through surface mapping. During the same period, major discoveries of petroleum and natural gas in the Four Corners region and at Lisbon Valley, Utah, and discovery of commercial potassium deposits at Cane Creek anticline increased the importance of gaining as much knowledge as possible about subsurface stratigraphy, deep-seated structure, and Paleozoic structural history. After realization that many of the geophysical anomalies arise from lithologic variations in the Precambrian basement, geological mapping and geophysical surveys of the exposed Precambrian rocks in the Uncompahgre uplift were conducted intermittently during 1961–64.

This report summarizes the main findings already published, interprets the geophysical anomalies in the western and southern parts of the region, not previously described, and presents a regional synthesis in the form of a basement map that was prepared on the basis of stratigraphic and structural studies by literally hundreds of geologists and of our interpretation of the geophysical data.

Gravity and magnetic surveys, when used in conjunction with available well data, provide much information on compositional and structural trends within the Precambrian crystalline basement, on depth to the basement, and, hence, on the thickness of the sedimentary column above the basement. They also provide information on lateral compositional variations within the sedimentary sequence—especially where major density contrasts are involved, as in the central Colorado Plateau—on the form and tectonic setting of the salt anticlines, and on general properties of Upper Cretaceous or Tertiary igneous intrusions and their tectonic setting. Some major deep-seated structures of the region were not detected by gravity and magnetic surveys because the displaced rocks have uniform density and magnetic properties, but those structures were identified by seismic surveys and drilling programs of private companies. Other major structures whose presence was originally postulated as a result of gravity and magnetic surveys have subsequently been proved by drilling, and still other major structures remain to be confirmed or disproved by future drilling or seismic surveys.

Earlier reports on geophysical investigations of specific areas are as follows (fig. 1): Uravan area (Joesting and Byerly, 1956, 1958), Lisbon Valley area (Byerly and Joesting, 1959), La Sal Mountains area (Case and others, 1963), the Upheaval Dome area (Joesting and Plouff, 1958), Moab-Needles area (Joesting and others, 1962, 1966), Salt Valley–Cisco area (Joesting and Case, 1962), Monument-Blanding area (Case and Joesting, 1961) and the northwestern Uncompahgre Plateau (Case, 1966). Reports of a more general nature include one on the salt anticlines and deep-seated structures (Joesting and Case, 1960), and one on Precambrian structures (Case and Joesting, 1962). Of special interest are the geophysical report by Steenland (1962) that covers part of the salt anticline region and the discussions of Steenland's paper by Joesting (1962) and Byerly (1962).

Principal facts for gravity surveys have been published for the Uravan area (Joesting and Case, 1970), the Moab-Needles area and Lisbon Valley

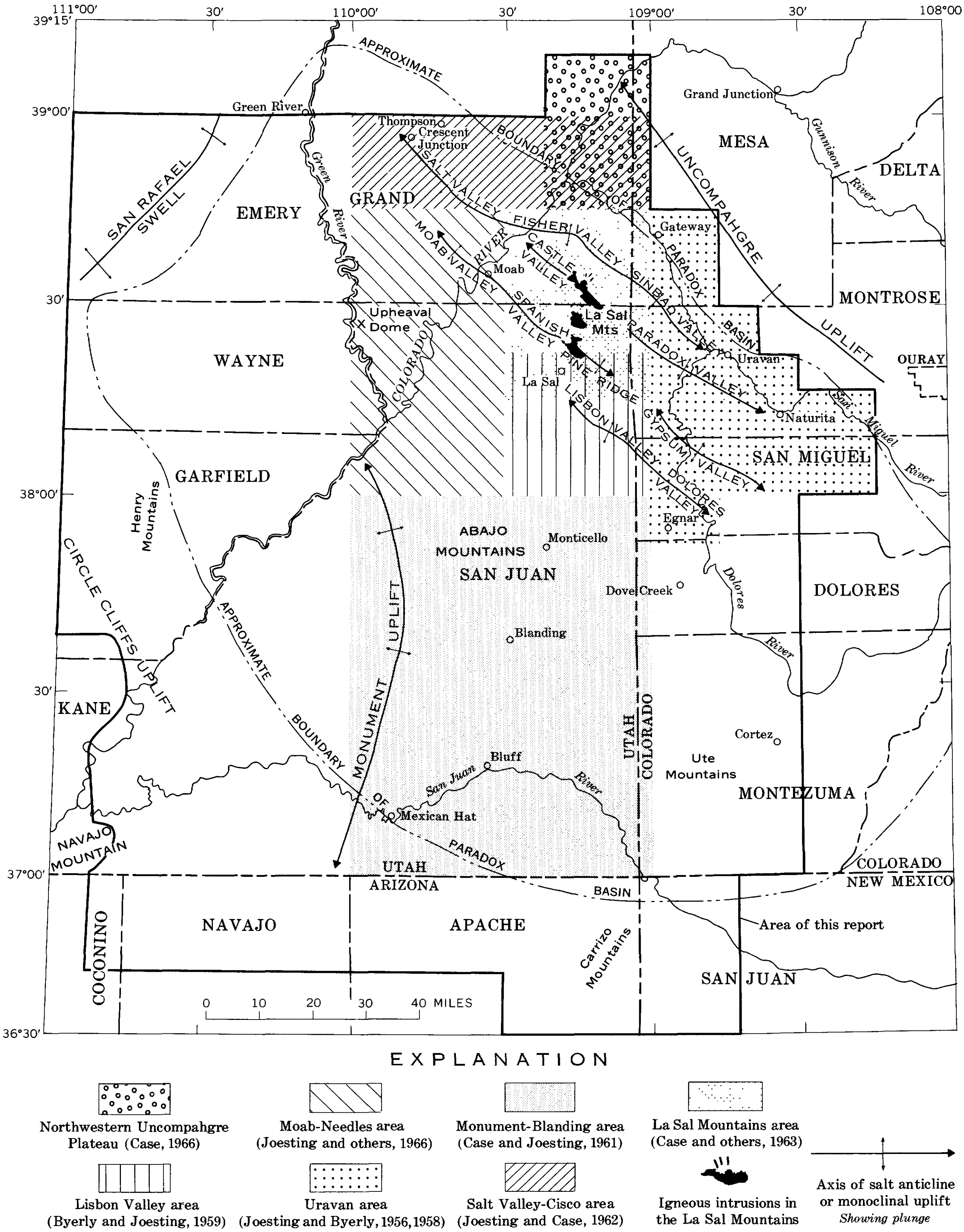

FIGURE 1.—Index map of parts of Colorado, Utah, Arizona, and New Mexico, showing region covered by gravity and magnetic surveys and areas covered by published geophysical reports.

area (Joesting and others, 1970), and the La Sal Mountains area (Joesting and Case, 1971).

The present investigation was directed by H. R. Joesting from its inception in 1953 until his death in May 1965. Many of the interpretive concepts are derived from discussion and correspondence with Joesting during the decade prior to his death.

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SUMMARY OF REGIONAL GEOLOGY

Huge monoclinal uplifts and intervening broad basins or structural terraces characterize those parts of the central Colorado Plateau covered by the regional gravity and aeromagnetic surveys. The uplifts are the Uncompahgre uplift in the northeastern part of the area, the San Rafael Swell in the northwestern part, the Circle Cliffs uplift in the southwestern part, the Monument uplift in the south-central part, and the Defiance (DeChelly) uplift in the southeastern part. A well-known prominent system of northwest-trending salt anticlines dominates the northeastern part of the region, in the Paradox basin (Kelley, 1955). High and rugged laccolithic mountain groups are distributed sporadically over the entire central Colorado Plateau region.

The region is underlain by a complex of Precambrian crystalline rocks which are similar to those elsewhere in the Southern Rocky Mountains. They consist of a wide variety of granites, gneisses and schists, and mafic intrusive rocks. Paleozoic carbonate rocks, clastic rocks, and evaporites attain an aggregate thickness of at least 17,000 feet. Mesozoic rocks consist of continental red beds and marine sandstones and shales that are at least 5,000 feet thick. The laccolithic mountains of latest Cretaceous or Tertiary age are composed of diorite porphyry and allied rocks. A few subsilicic mafic volcanic rocks, dikes, and plugs are present in the Four Corners area.

Many of the geologic features visible at the surface result from Laramide tectonism and igneous activity of Late Cretaceous or Tertiary time, but the region had a long and complex sedimentational and structural history prior to Laramide time (Fetzner, 1960; Baars, 1966). A major feature not exposed at the surface is the Paradox basin of Pennsylvanian age in which was deposited a thick sequence of evaporites and related rocks (Hite, 1968). Prior to Late Pennsylvanian, the region was deformed by large-scale faulting and warping near Lisbon Valley, in Paradox Valley, and elsewhere. The ancestral Uncompahgre uplift, one segment of the ancestral Rocky Mountains, was a dominant positive element during the Late Pennsylvanian and Permian, and the well-known salt anticlines achieved much of their growth during this time.

STRATIGRAPHY

The major stratigraphic units in the central Colorado Plateau are summarized in table 1, and are discussed briefly in the following paragraphs.

PRECAMBRIAN ROCKS

Within the region covered by these surveys, Precambrian rocks are exposed only in erosional windows on the Uncompahgre uplift. Precambrian rocks exposed near Gateway, Colo., consist of medium-grained gray granite, coarse-grained pink granite, hornblende and biotite schists and gneisses, and hornblende-rich dikes (Cater, 1955a). In the northwestern Uncompahgre uplift, Dane (1935, p. 20–24) reported several varieties of granite and biotite schist or gneiss. Also in the northwestern part of the uplift, south of Coates Creek, Precambrian rocks are dominantly coarse biotite quartz monzonite with subordinate amounts of gray biotite granite (Case, 1966). North of Coates Creek are several varieties of microcline-biotite gneiss, amphibolite, and gneissic granodiorite that represent a metasedimentary-metaigneous complex, much like the Vishnu Schist terrane of the Grand Canyon area. A metamorphosed mafic pluton, which ranges in composition from quartz diorite to gabbro, is exposed in the lower canyon of the Little Dolores River and in Marble Canyon. Metamorphic rocks were folded at least twice, and possibly three times, during the Precambrian (Case, 1966, p. 1430).

Samples of Precambrian rocks in the region, in addition to those from exposures, were obtained from deep drill holes and from inclusions in the younger igneous rocks. Most of these rocks are generally similar to those exposed on the Uncompahgre uplift, described in the preceding paragraph, but in south-

TABLE 1. — *Generalized stratigraphy of the central Colorado Plateau*

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

System	Group / Formation	Stratigraphic unit	Thickness (feet)	Lithology	Estimated density (g/cm^3)
Quaternary			0–500?	Alluvial sand, silt, and gravel, talus, and windblown deposits. Local glacial deposits.	2.2–2.4
Tertiary		Chuska Sandstone Green River Formation Wasatch Formation	0–2,000?	Sandstone, tuff, siltstone, and conglomerate.	2.3–2.4
Cretaceous		Mesaverde Group Mancos Shale	2,500?	Shale and siltstone.	2.3–2.45
		Dakota Sandstone Burro Canyon Formation	200?	Sandstone and conglomerate.	
Jurassic		Morrison Formation	540–850	Shale, siltstone, sandstone, and conglomeratic sandstone.	2.3–2.5
	San Rafael Group	Summerville Formation Curtis Formation Entrada Sandstone Carmel Formation	400–750	Sandstone and siltstone.	
Jurassic, Triassic(?), and Triassic	Glen Canyon Group	Navajo Sandstone Kayenta Formation Wingate Sandstone	550–1,100	Sandstone and siltstone.	
Triassic		Chinle Formation Moenkopi Formation	0–1,600	Shale, siltstone, sandstone, and conglomerate.	
Permian		Cutler Formation	0–8,000	Arkosic sandstone, quartzose sandstone, and shale.	2.58–2.65
Permian(?) and Pennsylvanian		Rico Formation	0–575	Limestone, shale, and arkosic sandstone.	
Pennsylvanian	Hermosa Formation	Upper member	0–2,500	Limestone, shale, and sandstone.	
	Hermosa Formation	Paradox Member	0–4,000+	Salt, gypsum, black shale, and limestone.	2.2–2.3?
	Hermosa Formation	Lower member	0–400	Limestone and shale.	2.6–2.7
		Molas Formation	0–150	Shale, sandstone, and limestone.	
Mississippian, Devonian, and Cambrian			0–4,200	Limestone, shale, dolomite, and sandstone.	
Precambrian				Quartz monzonite, granite, schist, gneiss, metagabbro, amphibolite, quartzite, and argillite.	2.6–3.2?

eastern Utah and northwestern Arizona, some drill holes have also penetrated quartzitic rocks. Diatremes in the southern part of the region contain inclusions of ultramafic and eclogitic fragments that came from levels in the crust and mantle that are deeper than the levels of the rest of the basement rocks. (See McGetchen, 1969, p. 194; Shoemaker, 1956.)

Densities and magnetic properties of Precambrian rocks are extremely variable (Case, 1966, p. 1430–1433). The gneisses have an average density of 2.7 g/cm^3 (grams per cubic centimeter) and an average susceptibility of 0.134×10^{-3} emu (electromagnetic unit); the quartz monzonite has an average density of 2.71 and an average susceptibility of 1.22×10^{-3} emu; and metagabbro and metadiorite have an average density of 2.88 g/cm^3 and an average susceptibility of 0.16×10^{-3} emu, but the measured susceptibility values are probably low, owing to alteration of magnetite in weathered specimens.

Rubidium-strontium and potassium-argon dates from Precambrian igneous rocks on the Uncompahgre Plateau indicate that the rocks range in age from 1,700 to 1,400 m.y. (million years) (Hedge and others, 1968; Mose and Bickford, 1969).

PALEOZOIC ROCKS

Cambrian strata of the region consist of sandstone, limestone, and dolomite which are thickest in the northwestern part and which thin out over the Defiance uplift in the southeastern part. Maximum thickness of the Cambrian, about 2,400 feet, occurs at the San Rafael Swell (Cooper, 1955; Baars, 1958; Lochman-Balk, 1956; Parker, 1961a).

Devonian beds consist of limestone, sandstone, and shale, and they range in thickness from 0 at the Defiance uplift to about 800 feet at the San Rafael Swell (Neff and Brown, 1958; Cooper, 1955; Parker, 1961a).

Mississippian beds are mainly limestone, and they range in thickness from 0 at the Defiance uplift to about 1,000 feet or more at the San Rafael Swell (Cooper, 1955; Neff and Brown, 1958; Parker, 1961a).

Cambrian through Pennsylvanian strata are absent over the northwestern Uncompahgre Plateau. Whether they were not deposited or whether they were deposited and subsequently eroded during Permian uplift of the ancestral Uncompahgre highland is unknown. Conglomerates that contain boulders with Mississippian fossils are exposed near the flank of the Salt Valley anticline (Dane, 1935, p. 24–25; Elston and Shoemaker, 1960, p. 53–54). This occurrence may indicate that Mississippian beds were deposited across the northwestern part of the Uncompahgre Plateau but were subsequently removed by erosion (Elston and Shoemaker, 1960, p. 53). In the subsurface, according to oil-scout reports, some lower to middle Paleozoic beds may be preserved along the southeastern part of the uplift.

Few data are available on densities of pre-Pennsylvanian sedimentary rocks of the region. Because the rocks contain a high proportion of limestone and dolomite, however, it seems likely that their average density is about 2.6 g/cm^3 or more. Thus, the density contrast between the pre-Pennsylvanian sedimentary rocks and the Precambrian basement is probably very small.

Upper Paleozoic units in the region, in ascending order, are the Pennsylvanian Molas and Hermosa Formations and the Permian and Pennsylvanian Rico Formation.

The lowest Pennsylvanian unit is the Molas Formation, a distinctive red-bed sequence, in part regolithic, of shale, sandstone, and limestone. It ranges in thickness from 0 to 150 feet in the Paradox basin (Wengerd and Matheny, 1958, p. 2064; Wengerd, 1962, p. 278–279). The Molas Formation is a useful stratigraphic marker in deep wells, but it has no significance in interpretation of the geophysical anomalies because of its relative thinness.

The Hermosa Formation consists of three members: a lower limestone member, the Paradox Member and an upper limestone member (Bass, 1944). The lower member (Pinkerton Trail Formation of Wengerd and Strickland, 1954, p. 2168–2169) is made up of limestone and shale, and it ranges in thickness from 0 to about 400 feet in the Paradox basin (Wengerd, 1962, fig. 24, p. 303). The Paradox Member (Paradox Formation of Wengerd and Strickland, 1954) ranges in thickness from 0 to 4,000 feet or more (Wengerd and Matheny, 1958, fig. 15, p. 2088; Wengerd, 1962, fig. 25, p. 305; Hite, 1968). The Paradox consists of evaporites, black shale, and limestone, and, because it forms the low-density cores of the salt anticlines, it has the greatest influence on the gravity anomaly map. Its average density probably ranges from about 2.2 to about 2.3 g/cm^3, judging from the relative proportion of evaporites, clastic beds, and limestone in the sequence (Case and others, 1963, p. 96). The upper member of the Hermosa (Honaker Trail Formation of Wengerd and Matheny, 1958) is made up of limestone, shale, and sandstone, and it ranges in thickness from 0 to about 2,500 feet. The Paradox Member and the upper member thicken northeastward and eastward toward the axial part of the Paradox Basin, just southwest of the Uncompahgre front.

The Rico Formation of Pennsylvanian and Permian(?) age is considered to be a transitional unit between the marine sedimentary rocks below and the terrestrial rocks above (Baker and others, 1927, p. 807). It consists of limestone, shale, and arkosic sandstone. Wengerd (1962, p. 284–287) included parts of the Rico with his Honaker Trail Formation. The thickness of the Rico ranges from 0 over the Uncompahgre uplift to about 575 feet in the area between the Green and Colorado Rivers (McKnight, 1940, p. 28). Its average density is estimated to be about 2.6 g/cm^3 (table 1).

The Permian red-bed sequence consists predominantly of arkosic sandstone, conglomerate, siltstone, and shale. In the northern and eastern parts of the central Colorado Plateau region, it consists of the undifferentiated Cutler Formation; in the central and southern parts of the region, it consists of several members of the Cutler Formation, including the Halgaito Tongue, Cedar Mesa Sandstone Member, and DeChelly Sandstone Member; and in the south and west, it consists of the Coconino and Kaibab Formations, which are approximate Cutler equivalents. In the Paradox basin the Permian beds range in thickness from about 1,000 feet at the San Rafael Swell to about 8,000 feet near the Uncompahgre front (Baars, 1962, p. 166, fig. 6). Permian beds are absent over the crest of the Uncompahgre uplift. Superimposed on the general northeastward thickening of the Cutler Formation are notable variations in thickness related to growth of the salt anticlines. Stratigraphic and geophysical evidence indicates that the Cutler thins toward the crests of the salt anticlines and thickens in areas between the anticlines (Shoemaker and others, 1958, p. 48–55; Elston and Landis, 1960, p. B261; Elston and Shoemaker, 1960, p. 53; Joesting and Byerly, 1958, p. 5; Baars, 1962, p. 164; Elston and others, 1962, p. 1869).

The effective density of the Rico and Cutler Formations and of the limestone of the Hermosa Formation is probably about 2.55 to 2.65 g/cm^3. Eight samples of limestone of the Hermosa near Big Indian Wash in the Lisbon Valley area have an average density of 2.65 g/cm^3 (Byerly and Joesting, 1959, p. 41). Saturated densities of 30 samples of the Cutler Formation collected near Gateway, Colo., average 2.58 g/cm^3 (Joesting and Byerly, 1958, p. 5).

MESOZOIC ROCKS

Mesozoic formations constitute the bedrock surface of most of the region (Williams, P. L., 1964; O'Sullivan and Beikman, 1963; Williams and Hackman, 1971; Haynes and others, 1972). The Triassic and Jurassic Systems were largely of continental deposition, although thin marine units of Jurassic age are present in the western part of the region (Carmel and Curtis Formations). The lower parts of the Cretaceous beds are continental (Dakota Sandstone and Burro Canyon Formation), the Mancos Shale is marine, and the Mesaverde Group is mixed marine and continental. The major Mesozoic units, in ascending order, are Moenkopi Formation, Chinle Formation, and Wingate Sandstone of Triassic age; the Kayenta Formation of Triassic(?) age; the Navajo Sandstone of Triassic(?) and Jurassic age; the San Rafael Group and the Morrison Formation of Jurassic age; and the Burro Canyon Formation, Dakota Sandstone, Mancos Shale, and Mesaverde Group of Cretaceous age. Their aggregate depositional thickness was on the order of 3,500 to 5,000 feet or more. Comprehensive descriptions of these rocks can be found in various reports on areal and regional geology listed in "References Cited."

These rocks probably range in density from 2.4 to 2.5 g/cm^3, as determined on the basis of their general lithologic similarity to Mesozoic beds in the Uravan and Lisbon Valley areas. The interval between the Chinle and Navajo(?) has a density of about 2.5 g/cm^3, as determined on the basis of gravity measurements at the top and bottom of San Miguel Canyon (Joesting and Byerly, 1958, p. 5). The Dakota and Morrison Formations in the Blanding basin, as shown by density profiles, range in average density from 2.3 to 2.5 g/cm^3.

TERTIARY AND QUATERNARY ROCKS

Tertiary beds consist of the Eocene Wasatch and Green River Formations along the Roan Cliffs in the extreme northern part of the region, and the Pliocene(?) Chuska Sandstone near the Defiance uplift in the extreme southeastern part of the region. Quaternary units are erratically exposed over the entire region. Eolian deposits probably are the most widespread deposits in the region, glacial deposits are present in the higher laccolithic mountains, and alluvial and colluvial fill is thick along the breached crests of the salt anticlines. For the most part, Tertiary and Quaternary beds have little or no influence on the geophysical anomalies of regional interest.

YOUNGER IGNEOUS ROCKS

Six groups of laccolithic mountains are prominent physiographic features of the region. These are the Henry Mountains (Hunt, 1953; Gilbert, 1877), the La Sal Mountains (Gould, 1927; Hunt, 1958; Carter and Gualtieri, 1957, 1958, 1965; Weir and others, 1960; Weir and Puffett, 1960), the Abajo Mountains (Gregory, 1938; Witkind, 1958, 1964), Sleeping Ute Mountain (Ekren and Houser, 1958, 1965), the Carrizo Mountains (Strobell, 1958), and Navajo Mountain, which is thought to be an unbreached laccolithic center (Hunt, 1956, p. 42; Condie, 1964). Briefly, each laccolithic group consists of one or more central stocks from which radiate clusters of laccoliths and sills. Dikes are common in some areas. Diorite porphyry is the dominant rock; monzonite porphyry, granodiorite, syenite porphyry, aegerine granite, and microgabbro are lesser constituents. The laccolithic mountains are latest Cretaceous (Shoemaker, 1954, p. 63) or Tertiary (Hunt, 1956, p. 42–45) in age.

Densities of these rocks range from about 2.45 to 2.75 g/cm^3 and average about 2.62 g/cm^3 (table 2). Magnetic susceptibilities range from 0 to 0.0045 emu and average about 0.0016 emu. Remanent magnetizations of undemagnetized specimens are generally weak and randomly oriented. Sampling is inadequate to determine if physical properties differ significantly from mountain group to mountain group.

TABLE 2. — *Mean magnetic susceptibility and mean saturated bulk density of samples from the Colorado Plateau laccolithic mountain groups*

Laccolithic mountain group	Mean magnetic susceptibility		Mean saturated bulk density	
	K (emu)[1]	Number of samples measured	Grams per cubic centimeter	Number of samples measured
La Sal Mountains	0.00160	115	2.61	108
Henry Mountains	.00063	28	2.64	28
Abajo Mountains	.00160	38	2.63	61
Carrizo Mountains	.0021	18	2.62	38
Sleeping Ute Mountain	.0017	29	2.58	35

[1]emu, electromagnetic unit.

Various eruptive centers, dikes, and volcanic collapse centers are sporadically distributed over the region. These include diatremes, mafic dikes, and alkalic dikes and sills (Hunt, 1956, p. 49–53; Shoemaker, 1956; Williams, Howel, 1936, p. 111–171). Their areal extent and volume are so limited that they have virtually no effect on the gravity maps and only small effects on the aeromagnetic maps. A few small sharp magnetic anomalies are caused by dikes, as discussed on page 26.

SUMMARY OF REGIONAL STRUCTURE

The structures of the central Colorado Plateau are those presently visible at the surface, which resulted largely from "Laramide" deformation or Laramide rejuvenation of older structures, those concealed, such as the Paradox basin, and related to late Paleozoic deformation, and those confined to the Precambrian basement. The regional structure is discussed in more detail by Baker (1935), Kelley (1955), Shoemaker (1954, 1956), and others.

The dominant Laramide structures are huge asymmetrical monoclinal uplifts that are separated by basins or structural terraces. Axes of the uplifts and of the monoclines bordering the uplifts are variable in trend. The Uncompahgre uplift and Circle Cliffs uplift trend generally northwest. The San Rafael Swell and parts of the Comb Ridge monocline, bordering the Monument uplift, trend northeast. The Monument uplift, the northern part of Comb Ridge monocline, and the Defiance uplift trend northward. Structural relief on Mesozoic reference horizons is about 6,000 feet from Blanding basin to the crest of the Monument uplift; about 8,000 feet from Thompsons, Utah, to the crest of the Uncompahgre uplift; about 4,000 feet from the San Rafael Desert to the crest of the San Rafael Swell; and about 7,000 feet from the axis of Henry basin to the crest of the Circle Cliffs uplift (Kelley, 1955; Shoemaker, 1954). In contrast, structural relief of the top of the Precambrian from the deep part of the Paradox basin across the Uncompahgre front is about 21,000 feet; the southwest flank of the uplift was an active tectonic boundary during the late Paleozoic, that was rejuvenated during the Laramide (Elston and others, 1962, p. 1874–1877; Joesting and Case, 1962, p. 1879; Case, 1966, p. 1425).

Salt anticlines of the region trend generally northwest, parallel to the front of the Uncompahgre uplift and to the axis of the deep part of the Paradox basin. They achieved most of their growth during late Paleozoic, but they continued to grow intermittently into the Mesozoic (Stokes, 1956; Cater, 1955b, 1970; Shoemaker and others, 1958).

The major features that formed in late Paleozoic were the Paradox basin and ancestral Uncompahgre uplift in the northeastern part of the region and the Defiance uplift in the southern part (Strobell, 1958). Minor positive areas may have been located near the present sites of the San Rafael Swell (Emery uplift, Wengerd, 1958, p. 109) and the Monument uplift (Lewis and Campbell, 1965, p. B33). The Nequoia arch (Schick Spur of Wengerd, 1958) is a prominent late Paleozoic ridge that trends northwest between the north end of the Monument uplift and the San Rafael Swell.

The Paradox basin is markedly asymmetrical; its deepest part lies close to the Uncompahgre front along the northeast flank of the basin. This deep inner basin is apparently separated from shallower parts to the southwest by a series of faults or warps that coincide with the southwest flanks of some of the larger salt anticlines, especially at Paradox, Gypsum, Lisbon, and Moab Valleys.

Pre-Pennsylvanian faults or warps, which have vertical displacements of as much as 5,000 feet, formed along the southwest flank of Paradox Valley salt anticline (Joesting and Case, 1960, p. B254; Case and others, 1963, p. 105; Parker, 1961a, fig. 2), and a dome or ridge in pre-Paradox beds, which has about 3,000 feet of structural relief from the graben to the crest of the ridge, borders the southwest flank of Lisbon Valley anticline (Parker, 1961b, fig. 1; Steenland, 1962). A deep-seated ridge in pre-Paradox rocks underlies the McIntyre Canyon area, which is northwest of Disappointment syncline between Gypsum Valley and the Dolores anticline (Joesting and Byerly, 1958, p. 9–10; Parker, 1961b, fig. 1). Other minor pre-Paradox structures have been found on the basis of drilling or have been postulated as a result of the geophysical surveys. These are discussed in subsequent sections.

Many concealed Precambrian lithologic discontinuities, some of structural origin, were recognized on the basis of analysis of combined drill data and gravity and magnetic anomalies. These are discussed in the sections dealing with interpretation of the geophysical data.

On the Uncompahgre Plateau, many Precambrian structural features, including large folds and some faults, have formed which are not reflected in "Laramide" structures — at most places the gently dipping Chinle Formation of Triassic age rests with extreme angular unconformity on highly deformed Precambrian metamorphic or igneous rocks. Some Precambrian faults, especially the Dry Gulch and the Little Dolores River faults, were rejuvenated during the Laramide (Case, 1966, p. 1430).

GEOPHYSICAL SURVEYS

Gravity surveys over the region are somewhat variable with respect to station spacing (pl. 1). In areas of special interest, such as in the Paradox basin, stations were spaced ½–2 miles apart; elsewhere in the region they were spaced 1–4 miles apart. Some areas of difficult access and some for which no base maps were available were not covered.

Worden gravity meters with scale constants of about 0.5 mgal (milligal) were used throughout the region. Elevation control was provided by bench marks, by photogrammetric elevations shown on topographic maps, by altimetric surveys, and, in a few areas, by transit traverses. On the whole, elevations are probably correct to within 20 feet, but in some areas where altimetric traverses were made through vertical ranges of several thousand feet or over horizontal distances of 5 miles or more, the elevations may be as much as 40 feet in error, equivalent to errors of 2.4 mgal in the Bouguer anomaly values.

Errors due to gravimetric drift are negligible in comparison with the errors in elevation. Instrumental drift was usually less than 1 mgal per day, and the corrected readings are thought to be generally accurate to within 0.2–0.3 mgal with respect to the base stations.

Terrain corrections were applied in all areas that had adequate topographic map coverage. Most terrain corrections were made through zones D–J of Hammer's (1939) tables. Corrections at some high mountain stations were extended to distances as great as 166.7 km (Case and others, 1963, p. 100). Terrain corrections were not made for some stations on the Grand Gulch Plateau and in parts of the San Rafael Desert, but terrain effects in those areas are small in comparison with the larger gravity anomalies of interest in regional interpretations. Specific areas in which terrain corrections were not made are shown in the reports that contain principal facts for gravity stations (Joesting and Case, 1970, 1971; Joesting and others, 1962, 1970).

Terrain corrections varied widely. Corrections of 0.5–5 mgal are common over the whole region, corrections of as much as 50 mgal were required at some high mountain stations where local relief was in excess of 7,000 feet, and corrections of 10–15 mgal were common at stations in deep canyons or at the edges of high mesas.

From considerations of the average errors in elevation, observed gravity, and terrain corrections, it is thought that the gravity anomaly contours are generally correct to within 2 mgal (pl. 1). In a few areas they may be in error by as much as 3–4 mgal. For more complete discussions of errors, see Byerly and Joesting (1959) and Case, Joesting, and Byerly (1963, p. 99–100).

The gravity anomalies shown on plate 1 are Bouguer anomalies for a reduction density of 2.5 g/cm^3 to which 300 mgal was added, so that all anomalies are positive.

Aeromagnetic surveys were made between 1953 and 1959 with a continuously recording fluxgate magnetometer (Balsley, 1952, p. 323–326) installed in a twin-engine plane flown at 150 miles per hour (pl. 2). East-west traverses were flown at 8,500 feet barometric elevation, except over the mountains. Flights were at 12,500 feet barometric elevation over the La Sal and Henry Mountains, 11,500 feet over the Abajo Mountains, and 10,000 feet over the Ute Mountains. Over the Lisbon Valley area of Utah and the adjoining Uravan area of Colorado, traverses were flown about 500 feet above the surface because the magnetic survey was flown in conjunction with a radioactivity survey. Flight lines were 2 miles apart in the Lisbon Valley and Uravan areas, 1 and 2 miles apart over the La Sal and Abajo Mountains, and 1 mile apart over the remainder of the study area.

INTERPRETATION OF THE GEOPHYSICAL MAPS[2]

The major anomalies shown on the gravity map (pl. 1) are the northwest-trending lows over the salt anticlines. General gravity highs are associated with each of the monoclinal uplifts, although local lows, as well as highs, are superimposed on the more general high over the Monument uplift. Small gravity highs of 5-10 mgal are present over the laccolithic mountains. A major regional low (G1) parallels the axis of Sagers Wash-Nucla syncline (Williams, P. L., 1964).

The gravity values, as expected from the structural depression of the Precambrian surface, are generally low in the basin areas, such as the Henry basin in the western part of the region and Blanding basin in the southeastern part of the region. In some basin and platform areas, however, local

[2]Specific gravity anomalies are located on plate 1 and magnetic anomalies are located on plate 2 by numbers which are shown on the maps near the crests or troughs of the anomalies or along zones of steepened gradient. These numbers are preceded, in text only, by G (gravity) or M (magnetic), which refer to plates 1 and 2, respectively.

anomalies are of such magnitude that sources other than structural relief must be dominant. Isolated highs and lows and zones of steepened gravity gradient that are apparently unrelated to surficial structure are present throughout the mapped area. Many of these can be related to density contrasts within the Precambrian basement and others to structural relief of the Precambrian or pre-Paradox surface. Even though the region covered by these gravity surveys is comparatively large, the gravity field probably has small regional isostatic variation, and most of the regional anomalies are caused by near-surface density contrasts or intracrustal density contrasts rather than by substantial variations in crustal thickness. Regional gravity anomalies appear to gradually become more negative eastward toward the Rocky Mountains (Woollard and Joesting, 1964). Gravity contours have about the same maximum values, 130–140 mgal, over the crests of the uplifts in the eastern, southern, central, and western parts of the region, where the sedimentary cover is thin and the Precambrian basement is shallow.

Magnetic anomalies of the central Colorado Plateau (pl. 2) can be placed, according to general pattern, age, lithology, and structural setting, into five categories:

1. The conspicuous ovoid or "birdseye" pattern of magnetic highs and lows that dominates most of the area is caused by diversely magnetized rocks of the crystalline Precambrian basement.
2. Many anomalies over the monoclinal uplifts are of higher amplitude and are bordered by steeper magnetic gradients than they are in structurally lower areas. Most of these are caused by Precambrian rocks.
3. The anomalies across the crests of the monoclinal uplifts are more heterogeneous than those over the adjacent structurally low areas, and this increased heterogeneity suggests a difference in Precambrian basement lithology, which may reflect the existence of Precambrian or late Paleozoic structural boundaries that were rejuvenated during the Laramide.
4. The near-linear zones of steepened magnetic gradients and lines of discontinuities of anomalies persist for many miles in parts of the region. These zones reflect major lithologic discontinuities within the Precambrian basement and probably indicate a fundamental fracture pattern of Precambrian age. Some of these fracture patterns are shown on plate 3, a map of basement structure and rock units inferred from gravity and magnetic anomalies and from drill-hole data. Dominant trends of these fracture zones are northwest, northeast, north, and east. This pattern has been detected in magnetic surveys in many parts of the world (Affleck, 1963).
5. The smaller, high-amplitude anomalies are associated with each of the laccolithic mountain groups, of latest Cretaceous or early Tertiary age, and with smaller intrusive dikes and sills of post-Mancos, probable Tertiary, age.

Contrasts in rock magnetization do not necessarily coincide with lithologic contacts, but one commonly makes this simplifying assumption in areas where the magnetic rocks are concealed. To a first approximation, major lithologic units may be crudely outlined by drawing contacts along zones of steepest magnetic gradient between anomalies (pl. 3).

Because the configuration of the Precambrian surface and the thickness of the sedimentary section are reasonably well known, it can be demonstrated that many of the positive and negative gravity anomalies must originate within the Precambrian basement. Many of the gravity anomalies areally relate to specific magnetic anomalies or groups of magnetic anomalies. Thus, gravity and magnetic anomalies over Precambrian rocks can be qualitatively classified according to the gross properties shown in table 3.

Note that the assignment of anomalies is subjective and that anomaly classifications are made on the basis of the character of adjacent anomalies. Thus, anomaly II in one region may not correlate with an anomaly II in a different region. We did not identify any anomalies that indicate sources of strongly magnetic but low- to moderate-density rocks.

TABLE 3.—*Key to anomaly classification*

[emu, electromagnetic unit; g/cm³, grams per cubic centimeter; >, greater than; <, less than]

Estimated range in apparent susceptibility, K (emu)	Rock properties and numerical key to plate 3	Estimated range in density (g/cm³)
$K>4\times10^{-3}$	Strongly magnetic and high density (I)	2.8 –3.2
$2\times10^{-3}<K<4\times10^{-3}$	Moderately magnetic and high density (II)	2.8 –3.2
	Moderately magnetic and intermediate density (III).	2.67–2.8
	Moderately magnetic and low density (IV)	2.55–2.67
$0=K<2\times10^{-3}$	Weakly magnetic and high density (V)	2.8 –3.2
	Weakly magnetic and intermediate density (VI).	2.67–2.8
	Weakly magnetic and low density (VII)	2.55–2.67
	Areas of no gravity data	
$K>4\times10^{-3}$	Strongly magnetic (VIII).	
2×10^{-3}	Moderately magnetic (IX).	
$0=K<2\times10^{-3}$	Weakly magnetic (X).	
	Areas of no magnetic data	
	High density (XI)	2.8 –3.2
	Intermediate density (XII)	2.67–2.8
	Low density (XIII)	2.55–2.67

SOME MAJOR GRAVITY ANOMALIES IN THE NORTHERN PART OF THE REGION

In the northern part of the region (pl. 1), the decrease in gravity anomaly values from Reef monocline across the San Rafael Desert to Salt Valley anticline can be attributed (1) to increasing depth of the Precambrian surface from 3,000 to 4,000 feet below sea level at the foot of Reef monocline to perhaps 10,000 feet below sea level at Salt Valley anticline; (2) to increasing thickness of Paradox evaporites from about 500 feet at the San Rafael Swell to 3,500 feet or more at Thompsons; and, possibly, (3) to decreasing average density of the Precambrian basement toward Salt Valley anticline. The gravity low (G2) that trends northeast from Hanksville to Keg Knoll may be related to local depositional salt thickening in the Fremont Accessway (Wengerd, 1962, fig. 25, p. 305).

A very prominent zone of steepened gravity gradient (G3) extends eastward, or southeastward, from Mineral Point near the Green River to Spanish Valley, then turns abruptly northeast, across the northwest flank of the La Sal Mountains (G4), and then turns southeast, parallel to North Mountain and the southwest flank of the Paradox Valley anticline (G5). The zone serves to separate the deeper part of the Paradox basin into two parts — a southern, shallower part and a northern, deeper part. The zone of steepened gravity gradient is caused by (1) thicker salt to the north of the zone of steepened gradient, (2) deeper Precambrian basement to the north, and (3) denser Precambrian rocks to the south of the zone of steepened gradient, especially in the area south of Upheaval Dome, near Kane Springs Canyon (Joesting and others, 1966, p. C14–C15), and beneath the La Sal Mountains (Case and others, 1963, p. 102–104).

In the northeastern part of the central Colorado Plateau, the regional gravity low (G1) that coincides approximately with the Sagers Wash–Nucla syncline (Williams, P. L., 1964) marks the position of the deepest part of the Paradox basin. In this area, the surface of the Precambrian rocks is probably as much as 10,000–13,000 feet below sea level (pl. 3).

Discontinuous highs (G55) and lows (G56) in the area between the Henry basin and the Lisbon Valley anticline are related primarily to density contrasts within the Precambrian basement, but may also reflect local depositional thickening and thinning of the Paradox evaporites. The north-trending high (G6) near Cedar Point and Bert Mesa, east of the Henry Mountains, is probably caused by a block of dense but weakly magnetized basement rock.

PARADOX BASIN

GRAVITY ANOMALIES RELATED TO SALT ANTICLINES IN THE PARADOX BASIN

In the Paradox basin the gravity lows over the salt anticlines vary considerably in amplitude (1) as a function of the height of the salt column above the original level of the mother salt sequence, (2) as a function of the length and breadth of the salt core, (3) as a function of the density contrast between the salt in the core and the adjacent sedimentary rocks, and (4) as a function of the thickness of cover of rocks above the crest of the salt core.

The line of anticlines to the northeast, near the Uncompahgre front and the deepest part of the Paradox basin, is made up of the Salt Valley, Fisher Valley, and Sinbad Valley anticlines (fig. 2). A residual negative gravity anomaly (G7) of −26 to −28 mgal is found over Salt Valley anticline; thus, assuming a density contrast of −0.35 g/cm^3, the amplitude of the salt core is about 8,000 feet (Joesting and Case, 1962, fig. 6, p. 1888). The residual anomaly (G8) over Fisher Valley is about −18 mgal; assuming a density contrast of −0.25 (in keeping with the higher proportion of clastic beds in the evaporite sequence near the Uncompahgre front), the amplitude of the salt core is about 10,000 feet (Case and others, 1963, fig. 38, p. 108). Using similar assumptions, we determined that the amplitude of Sinbad Valley anticline (G9) is on the order of 10,000–11,000 feet (Case and others, 1963, p. 106–107; Shoemaker and others, 1958, p. 43–45). Gravity and magnetic contours suggest little or no deep-seated structural control for the position of this system of salt anticlines. However, the presalt basement could be displaced by as much as 1,000 feet, or even more, without giving rise to an identifiable gravity or magnetic anomaly, if the density and susceptibility of the presalt rocks are the same on both sides of the deep-seated zone of displacement.

The adjacent anticlinal system to the southeast consists of Castle Valley and Paradox Valley anticlines (figs. 3, 4). Analysis of the residual gravity anomaly (G10) of —16 mgal over Castle Valley indicates that the amplitude of the salt core is about 7,000 feet, if the density contrast is −0.30 g/cm^3 (Case and others, 1963, p. 107–108). Thickened salt of the Castle Valley mass extends under the northwestern part of the North Mountain group of the La Sal Mountains and presumably connects at depth with thickened salt of the Paradox Valley anticline (Shoemaker and others, 1958, p. 45). Assuming density contrasts that range from −0.42 to −0.3 g/cm^3, Joesting and Byerly (1958, p. 14–15) computed the amplitude of the salt core of Paradox Valley anticline (G11) to be 9,000–10,500 feet (fig. 4).

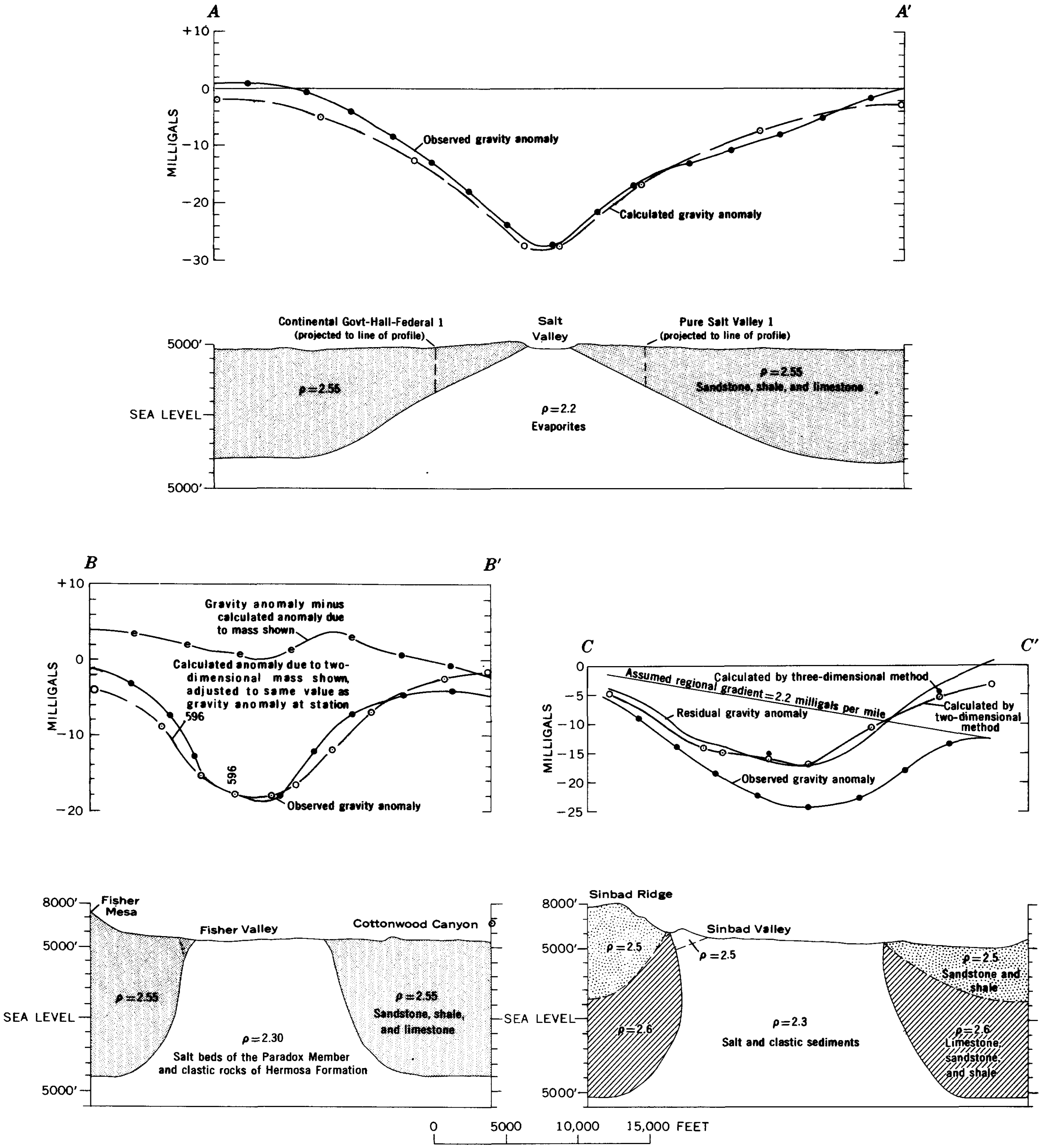

FIGURE 2. — Interpretation of gravity anomalies over Salt Valley (A–A'), Fisher Valley (B–B'), and Sinbad Valley (C–C') anticlines. ρ, density, in grams per cubic centimeter. Location of profiles is shown on plate 1.

Subsequently, deep wells drilled near the southwest flank of the anticline and in the core of the anticline indicate that the amplitude of the salt core is at least 9,000 feet (Elston and others, 1962, p. 1874).

A fault or warp in pre-Paradox rocks, which has at least 5,000 feet of displacement, borders the southwest flank of Paradox Valley anticline. A major structure at this position was first postulated on the basis of the very steep regional gravity gradient (G5) across the present site of the salt anticline (Joesting and Byerly, 1958, pl. 3), and in a summary article (Joesting and Case, 1960, p. B254–B255), we inferred a major deep-seated structural boundary. Subsequently, deep drill holes confirmed the major fault or warp (Case and others, 1963, p. 104, fig. 34) which evidently controlled the position of the salt anticline. Elongated igneous intrusions at North Mountain are on the same trend, and it seems reasonable to infer that the same deep-seated zone of displacement served as a partial control for the emplacement of the igneous intrusions, and that the final form of the intrusions was controlled by the salt anticlines, as pointed out by Gould (1927). No gravity or magnetic evidence indicates a deep-seated structure associated with Castle Valley salt anticline, but it is on strike with North Mountain and Paradox Valley to the southwest which appear to be controlled by presalt displacements. Thus, a deep-seated fault or warp with lesser displacement under Castle Valley may be postulated.

A third major line of salt anticlines extends from southwest of Crescent Junction, Utah, along Moab and Spanish Valleys to Gypsum Valley, Colo. (figs. 5, 6). A small, rather deeply buried salt anticline (G12) near Tenmile Canyon (T. 23 S., Rs. 18 and 19 E.) has been inferred on the basis of a 6- or 7-mgal gravity low (Joesting and Case, 1962, fig. 7, p. 1888). This salt mass is on the same trend as the well-known Moab Valley–Spanish Valley salt anticline. If there is a density contrast of -0.35 g/cm^3, the amplitude of the salt core of Moab Valley anticline (G13) is about 8,000 feet (Joesting and others, 1966, p. C16–C17). Farther southeast, at South Mountain, igneous intrusions are elongated northwest, and thickened salt is inferred to be present at depth beneath the igneous rocks. A small salt anticline (G14) near Pine Ridge has been inferred on the basis of surficial anticlinal structure and associated gravity low (Shoemaker and others, 1958, fig. 1, p. 40; Byerly and Joesting, 1959, p. 48–49). Assuming a density contrast of -0.4 g/cm^3, Byerly and Joesting (1959, p. 48–49) inferred that the amplitude of the salt mass at Pine Ridge is about 3,500–4,000 feet, and that its top is about 3,000–4,000 feet beneath the surface. Subsequently, the inferred salt anticline was confirmed by drilling for potash (Carter and Gualtieri, 1965, p. 28–29). Graticule analyses of the Gypsum Valley salt anticline (G15) were not made, because of the difficulty in evaluating which regional gradient to remove, but judged from the amplitude of the gravity anomaly, the amplitude of the salt anticline is on the same order as those of the other large salt anticlines of the region. (See Steenland, 1962, fig. 13, p. 88.)

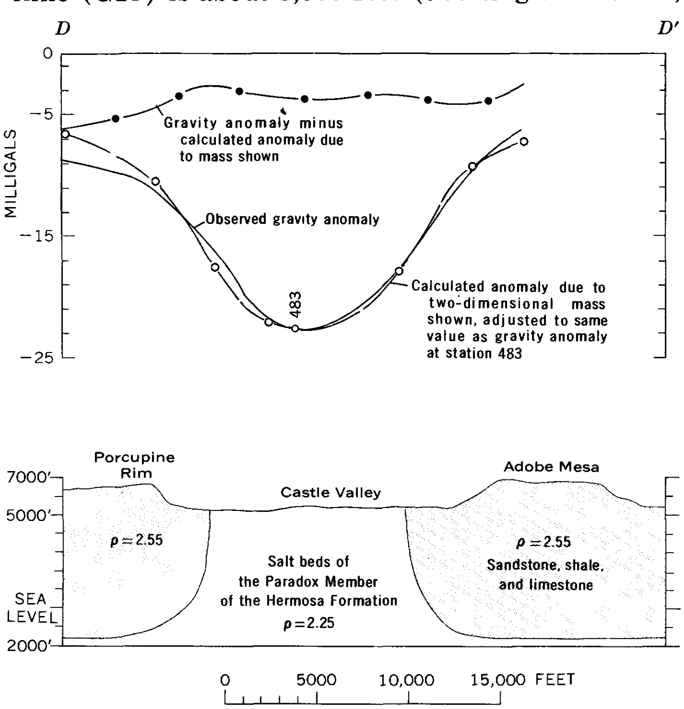

FIGURE 3.—Interpretation of the gravity anomaly over Castle Valley (D–D') anticline. ρ, density, in grams per cubic centimeter. Location of profile is shown on plate 1.

A fourth system of salt anticlines is made up of Cane Creek, Lisbon Valley, and Dolores anticlines. Cane Creek anticline has little gravity expression (G16; pl. 1). Lisbon Valley anticline is outlined by a well-defined gravity low (G17) of about -18 mgal. Analysis of a three-dimensional model of the anticline, assuming a density contrast of -0.375 g/cm^3, indicated that the amplitude of the salt core is on the order of 5,000 feet (Byerly and Joesting, 1959, p. 46–48). Analysis of a two-dimensional anomaly (fig. 7) indicated an amplitude of 4,000 feet. Subsequently, data from deep drill holes indicated that the structural relief across the southwest margin is about 4,500 feet (Parker, 1961b, p. 165; Elston and Shoemaker, 1961), and the relief across the northeast flank, across the Lisbon fault, is on the order of 8,000–8,500 feet. Structure contour maps of the top of the salt, prepared by Byerly and Joesting (1959, fig. 19), compare favorably with those based on later well data presented by Parker (1961b, fig. 2). Evidently a graben or depression underlies the salt anticline, and a dome or ridge in pre-Pennsylvanian rocks with at least 2,000 feet of structural relief borders the southwest flank of the deep-seated graben (pl. 3; Parker, 1961b, figs. 1, 9). This presalt high is not expressed by the gravity or magnetic contours, and, thus, it must be inferred that there is only a small density and magnetic contrast between the Precambrian rocks that compose the core of the dome and the Paleozoic and Precambrian rocks adjacent to the dome. A coarse biotite quartz monzonite was penetrated by a deep drill hole that reached the Precambrian basement. This deep-seated

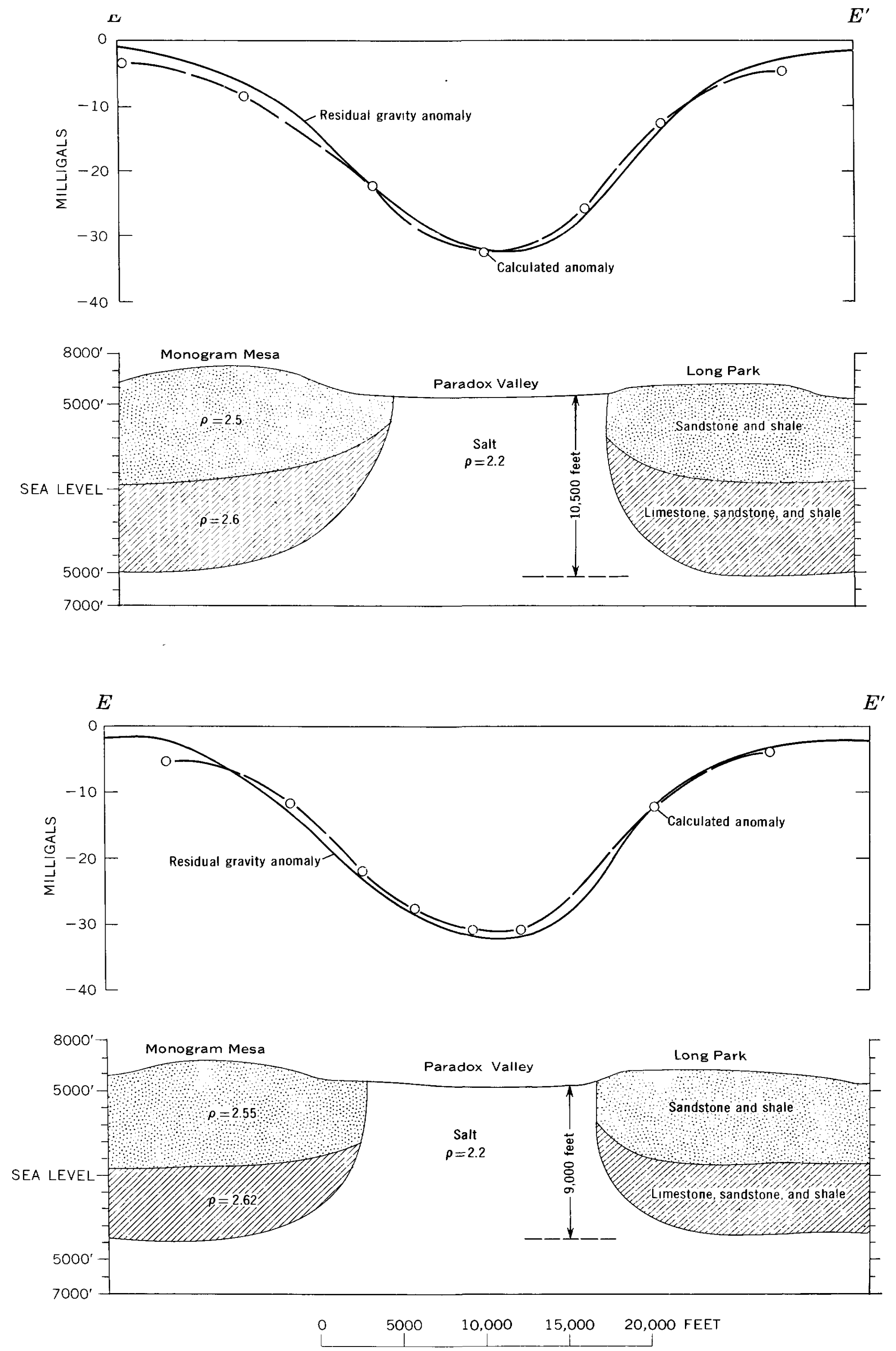

FIGURE 4. — Interpretation of the gravity anomaly over Paradox Valley (*E–E'*) anticline. ρ, density, in grams per cubic centimeter. Location of profile is shown on plate 1.

structure serves as primary control for accumulation of petroleum and gas in Mississippian and Devonian rocks in the Lisbon oil field. It was apparently detected by seismic methods (Parker, 1961b, p. 163).

Dolores anticline is on trend with the Lisbon Valley anticline (Williams, P. L., 1964), but structural relief on top of the salt at the Dolores anticline is much lower than that on the Lisbon Valley anticline,

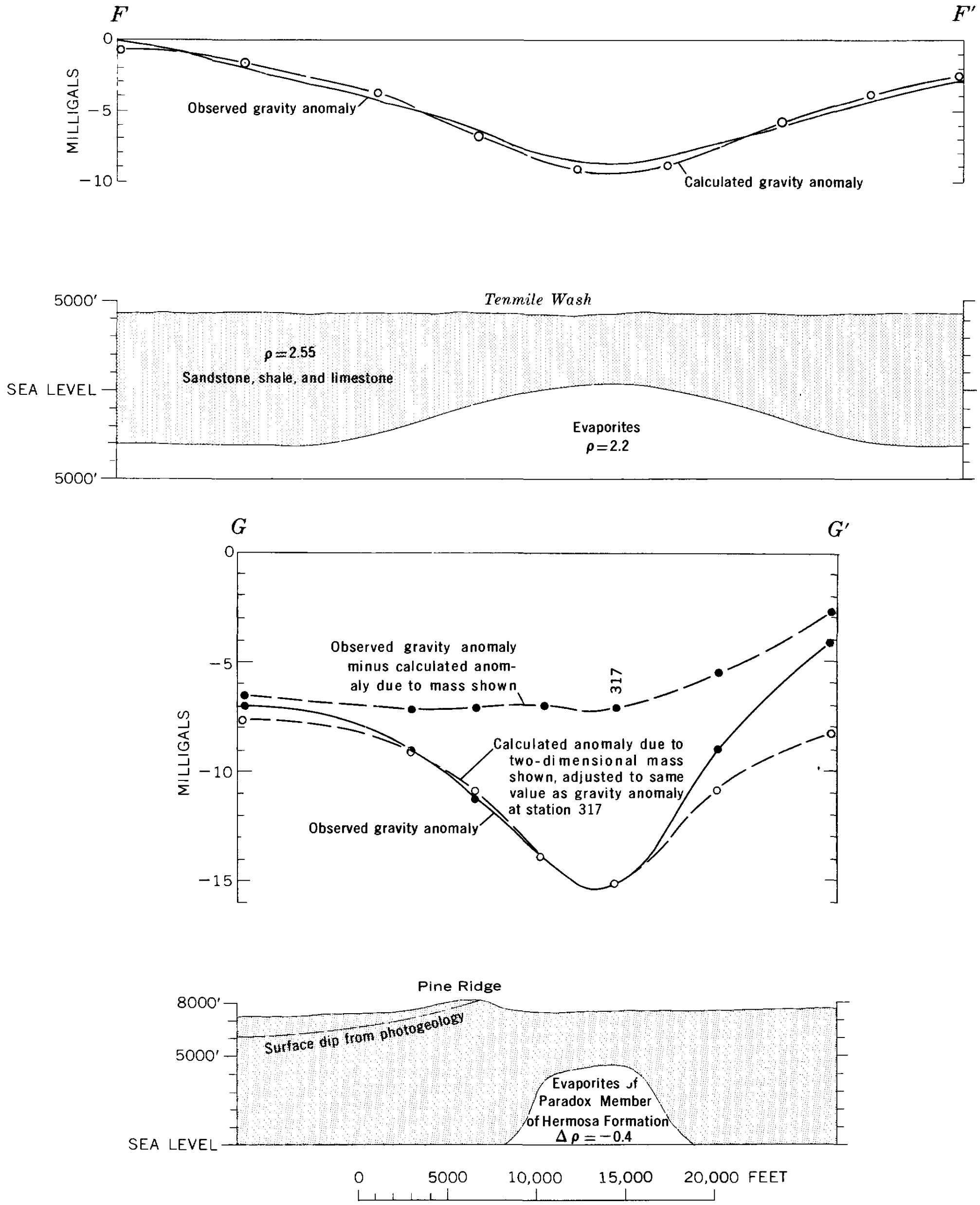

FIGURE 5. — Interpretation of the gravity anomalies over Tenmile Wash (*F–F'*) and Pine Ridge (*G–G'*) anticlines. ρ, density, in grams per cubic centimeter; $\Delta\rho$, density contrast. Location of profiles is shown on plate 1.

according to structure contour maps of Elston and Shoemaker (1961). The total relief across the southwest flank is about 1,000 feet, and across the northeast flank, from Disappointment syncline to the crest of the anticline, it is about 4,000 feet. According to Parker (1961b, fig. 2), however, the relief across the northeast flank is about 5,300 feet. A rather broad gravity low (G18) is present along the axis of the anticline, but it may be related in part to intrabasement density contrasts, as well as to local thickening of salt.

Other anticlinal or domal structures believed to be salt anticlines are Shafer dome, Lockhart anticline, Rustler dome, Gibson dome, and Meander anticline (Williams, P. L., 1964). No significant gravity lows have been detected over these structures, but this absence of detected lows may be attributed to the masking influence of regional gravity gradients related to intrabasement density contrasts and to rather large probable errors in elevation and in terrain corrections.

A local gravity high (G24) is located near Lockhart basin, a structural basin at the southwest end of Lockhart anticline.

The origin of Upheaval Dome, near the Green River, has long been controversial, and various hypotheses were summarized by Mattox (1968). A small gravity high of 2 mgal on which is superimposed a smaller low of 1 mgal is present over the dome (G19). Terrain corrections for some stations at the dome were in excess of 8 mgal, and, thus, it is doubtful whether the apparent anomalies of 1–2 mgal are of significance in determining if the dome is a true salt dome or if it is a cryptovolcanic dome.

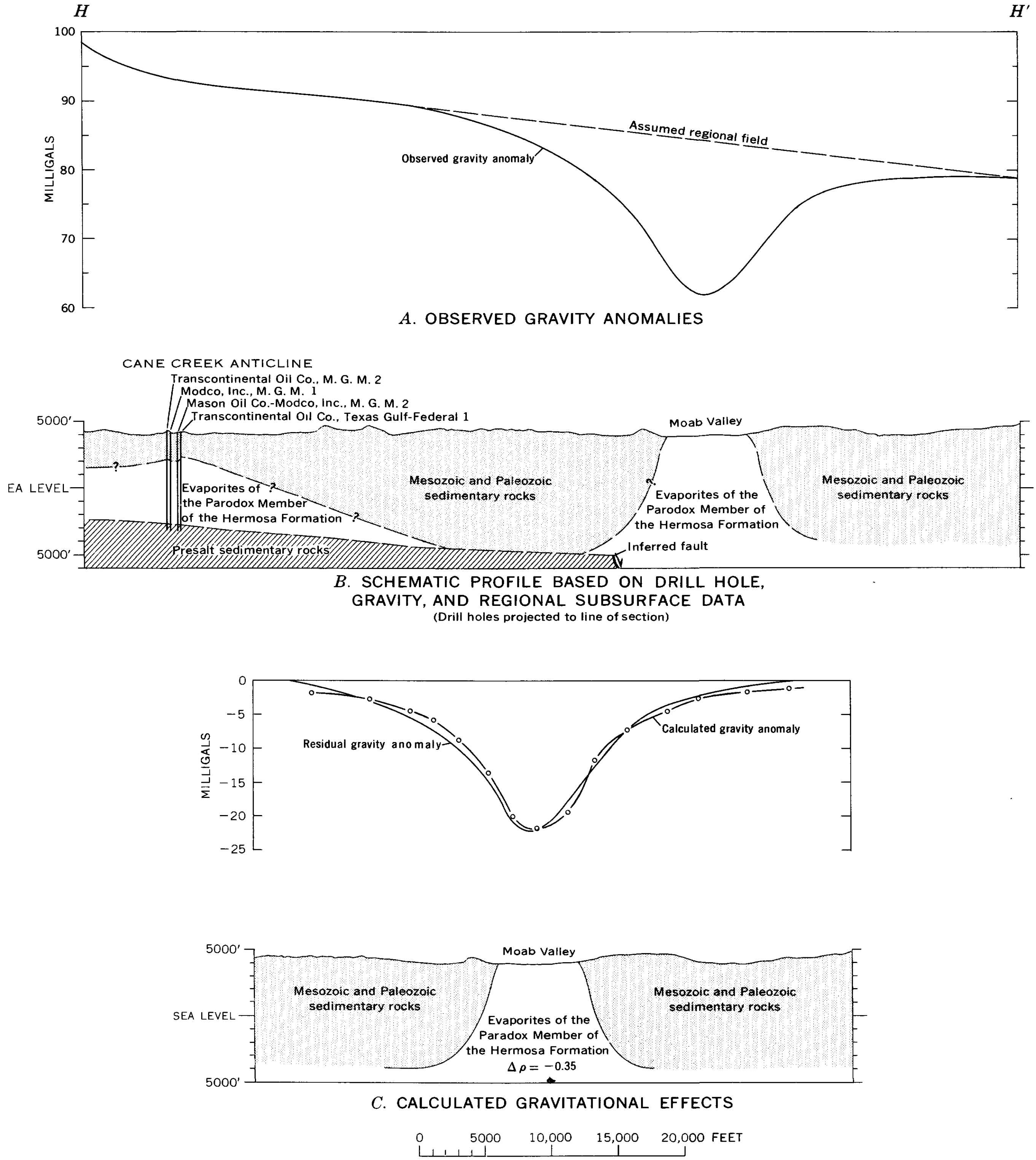

FIGURE 6. — Interpretation of the gravity anomaly over Moab Valley (*H–H'*) anticline. $\Delta\rho$, density contrast. Location of profile is shown on plate 1.

(For a more complete discussion, see Joesting and Plouff, 1958; Joesting and others, 1966, p. C12–C14, C17.) We believe Upheaval Dome to be a salt dome that has no Paleozoic or younger igneous intrusions associated with it.

OTHER GEOPHYSICAL ANOMALIES IN THE PARADOX BASIN

[Pls. 1 and 2]

In the Paradox basin east of the Colorado River are several conspicuous gravity and magnetic highs. One (M1, G57), near Kane Springs Canyon and Hatch Point, is very similar to a large pair of anomalies near Upheaval Dome (M2, G22) and Grays Pasture (M3, G23) which are probably caused by mafic intrusions in the Precambrian, possibly gabbroic rocks. To the south, from Bucks Flat westward across Harts Point to Salt Creek, a zone of magnetic highs (M4) locally coincides with a zone of gravity highs (G20) of low amplitude which are probably caused by intermediate to mafic rocks, again possibly dioritic to gabbroic.

Several prominent zones of magnetic discontinuities trend northeast across the area. One zone (M5), which is subparallel to the Colorado River, is a lineament, possibly a fault, along which left-lateral displacement may have occurred, if the mafic basement rocks at Grays Pasture (M3) and Hatch Point (M1) were once alined. Another gravity (G4) and magnetic lineament (M6) extends northeast from the area just west of the La Sal Mountains into the Uncompahgre front near Gateway, Colo., where the magnetic anomalies are apparently offset left laterally. Still a third zone of magnetic (M7) and gravity (G21) discontinuity, less well defined, extends northeast from the central part of Gypsum Valley to the Uncompahgre front near Pinto Mesa.

More conspicuous in the area, however, are the northwest trends of the magnetic contours, which clearly indicate the dominance of northwest-trending structure in the basement.

The zone of magnetic highs (M8) along the southwest flank of Gypsum Valley was interpreted to indicate a basement ridge or structural high under the Disappointment Valley–McIntyre Canyon area (Joesting and Byerly, 1958, p. 1–11), and this interpretation was subsequently demonstrated by drilling (Joesting and Case, 1960, p. B254). A prominent low (M9) over Big Gypsum Valley may be a polarization low related to the magnetic highs to the southwest. In contrast, the basement high or ridge southwest of Lisbon Valley, as outlined by drill holes (Parker, 1961b), is not indicated by the

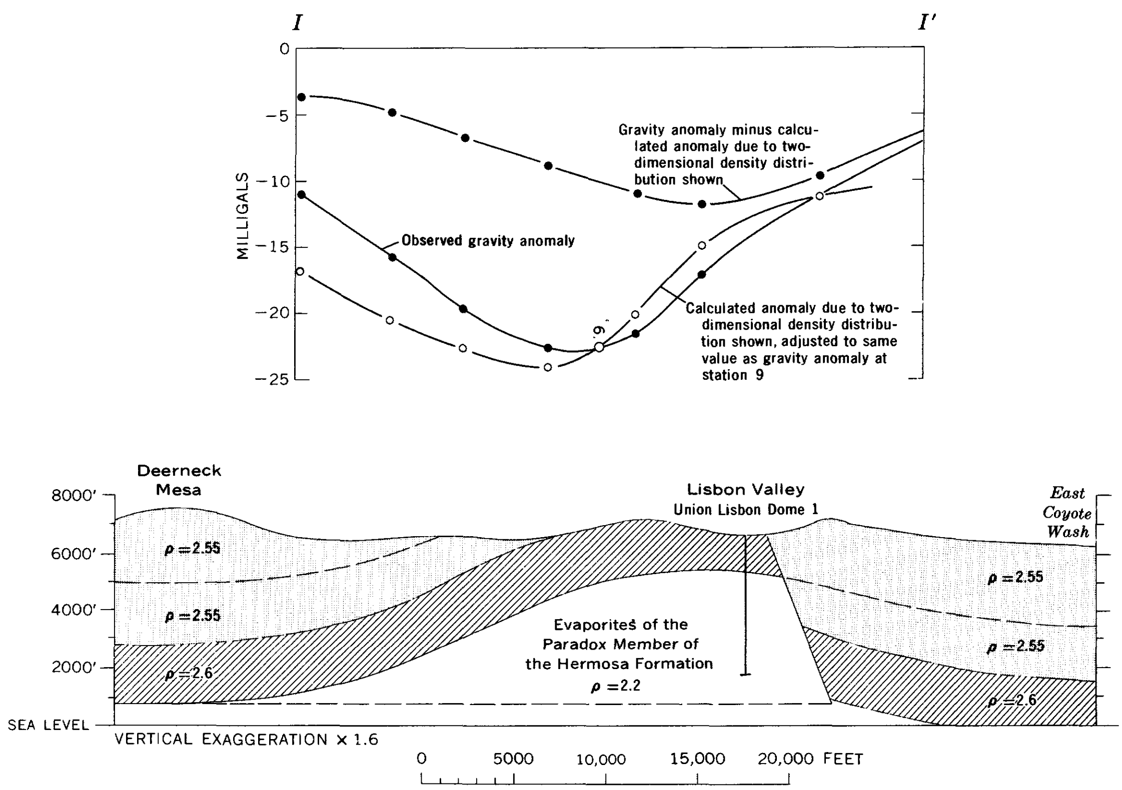

FIGURE 7.—Interpretation of the gravity anomaly at Lisbon Valley (*I–I′*) anticline. ρ, density, in grams per cubic centimeter. Gravity anomalies calculated for a reduction density of 2.67 g/cm^3. Location of profile is shown on plate 1.

gravity or magnetic anomalies; hence, little if any density and magnetic contrast exists between the Precambrian and lower Paleozoic rocks in that area. The basement fault bordering the southwest flank of Paradox Valley (Joesting and Case, 1960, p. B254–B255) is indicated by the steepened gravity gradient (G5) but is only weakly suggested by the magnetic data.

A broad magnetic high (M10) near Professor Valley and Yellow Cat dome may be related to a moderately magnetic but low-density basement rock mass. Inasmuch as the nearest magnetic rocks exposed to the east on the Uncompahgre Plateau are composed of biotite quartz monzonite of Precambrian age, it may be inferred that these magnetic anomalies are likewise caused by quartz monzonite. A steep gradient (M11) on the south flank of these anomalies may be caused by a basement fault zone.

UNCOMPAHGRE UPLIFT

[Pls. 1 and 2]

Only a few gravity traverses extended to the crest of the Uncompahgre uplift, inasmuch as base maps were available only for the northwest end of the uplift. Several profiles extend partly across the southwest front of the monocline. All the gradients are steep, and all the gravity anomaly values increase toward the uplift. An analysis of the gravity profile across the buried Uncompahgre front, near Cisco, Utah (profile *J–J′*, fig. 8), indicates that the relief on the Precambrian basement surface from near Sagers Wash to Cisco is about 12,000 feet (Joesting and Case, 1962, p. 1885–1887). No attempt was made to obtain a perfect fit between observed and computed anomalies because of the many uncertainties in assumed densities and orientations of geologic contacts. From Cisco to the crest of the uplift near the Utah-Colorado line, the relief of the top of the Precambrian is about 7,000 feet; thus, the total relief is on the order of 19,000 feet. The total gravity relief from the axis of Sagers Wash syncline to the crest of the uplift is about 50 mgal (profile *K–K′*). The gravity relief is caused by several geologic features: (1) a relief of 15,000–19,000 feet on the Precambrian surface, (2) the presence of several thousand feet of evaporites near the Dolores River, which wedge out against the Uncompahgre front, and (3) density contrasts within the Precambrian rocks of the uplift; biotite gneiss and amphibole gneiss and gabbroic rocks near the crest of the uplift are apparently more dense than granitic rocks on the southwest flank of the uplift (fig. 8). Other incomplete gravity profiles, near Gateway, Colo., and Tabeguache Creek (near Uravan), Colo., merely indicate that the front of the uplift is steep, as was already known from surficial geology (Cater, 1955a; 1970, pl. 1).

Although only a small segment of the Uncompahgre uplift was covered by the aeromagnetic surveys (pl. 2), the anomalies there are of considerable significance because they have been correlated, in part, with the principal types of well-exposed Precambrian rocks (Case, 1966).

In the extreme northwestern part of the uplift, conspicuous positive magnetic anomalies (M14) occur over a batholith of magnetic biotite quartz monzonite which is exposed along the southwest flank of the uplift in the Spring Canyon–Ryan Creek area. Similar large positive anomalies (M15) were found over the part of the batholith that is exposed near the southwest end of Unaweep Canyon (Joesting and Byerly, 1958, pl. 2, and fig. 3, p. 8–9). These anomalies are produced by a combination of structural relief of the Precambrian basement along their southwest flanks and of magnetic contrasts within the basement along the northeast flanks of the anomalies; weakly magnetic metamorphic rocks occur northeast of the batholith. Magnetic susceptibilities of fresher samples of the frontal batholith range from 2×10^{-3} to 3.5×10^{-3} emu. From the presence of two magnetic highs (M16) and the absence of a gravity high, another belt of concealed quartz monzonite is inferred to extend from the region north of the Little Dolores River in Colorado to the region around Harley Dome, Utah.

A prominent gravity and magnetic high (M12, G25) is found over the Little Dolores River metagabbro pluton near Marble Canyon. The combined gravity and magnetic (M13, G26) data indicate that a concealed mafic pluton causes geophysical highs in Tps. 20 and 21 S., R. 24 E., similar to anomalies of higher amplitude over the exposed Little Dolores River pluton. A small sharp aeromagnetic high (M17) in T. 13 S., R. 104 W., Colorado, probably is related to a concealed mafic or ultramafic rock mass. Elsewhere along the uplift and along the buried extension of the uplift, Precambrian rocks are inferred to be dominantly metamorphic types with relatively low susceptibility. Analyses of three magnetic profiles across the Uncompahgre front are shown in figure 9.

Inasmuch as the cover of nonmagnetic sedimentary rocks is thin over the uplift, one can estimate the depth to the Precambrian surface rather closely by use of regional isopach and structure maps. In a previous map (Case, 1966, fig. 11) the sedimentary cover was "stripped" from the northwestern part of the uplift to indicate the inferred rock types that cause the geophysical anomalies and to show the structure of the Precambrian surface.

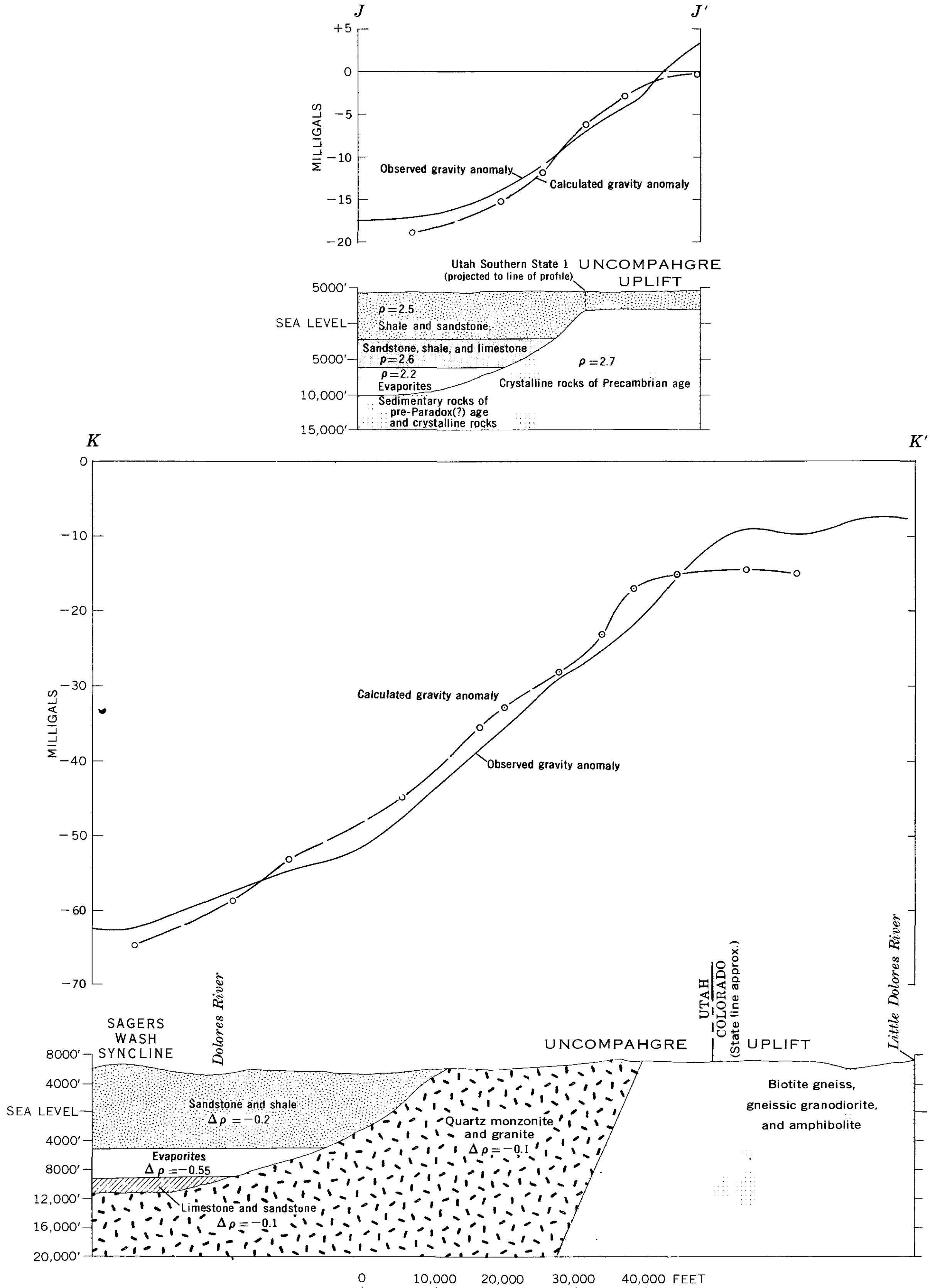

FIGURE 8. — Interpretation of gravity anomalies across the Uncompahgre front. *J–J'*, near Cisco; *K–K'*, Sagers Wash syncline to Little Dolores River. ρ, density, in grams per cubic centimeter; $\Delta\rho$, density contrast. Location of profiles is shown on plate 1.

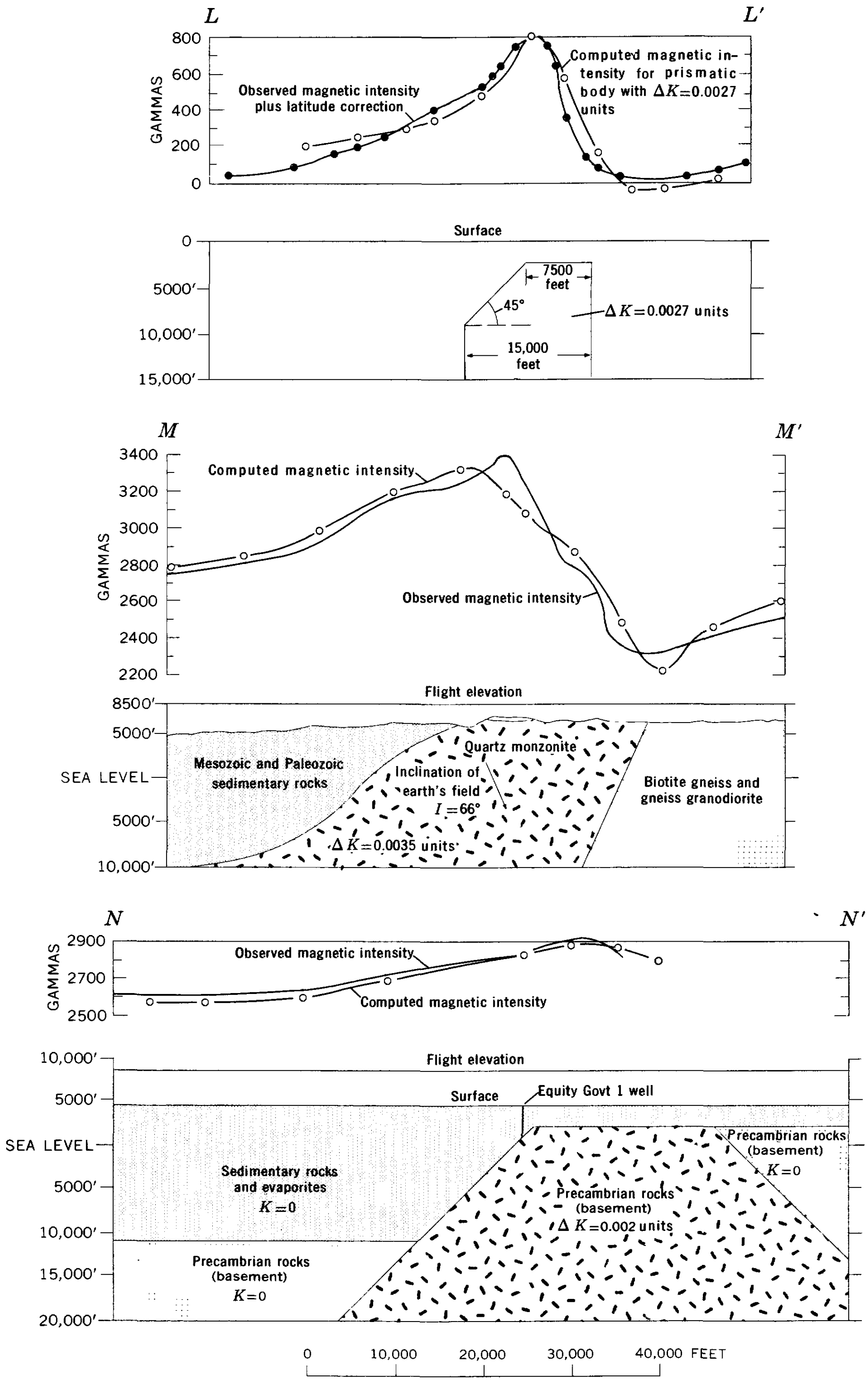

FIGURE 9. — Interpretation of magnetic profiles across the Uncompahgre front. *L–L'*, near Gateway; *M–M'*, near Ryan Creek; *N–N'*, near Cisco. ΔK, magnetic susceptibility contrast; K, magnetic susceptibility, in emu. Location of profiles is shown on plate 2.

The deeper part of the Paradox basin immediately southwest of the Uncompahgre front is generally characterized by relatively flat magnetic gradients that reflect the greater depth to the Precambrian surface. However, the flat or gentle magnetic gradients indicate, in part, that the basement is nearly nonmagnetic; thus, we postulate that the deepest part of the basin may be underlain by a thick sequence of weakly metamorphosed or unmetamorphosed Precambrian sedimentary rocks. Greater heterogeneity of the magnetic anomaly pattern over the uplift than over the adjacent deep Paradox basin suggests that the Uncompahgre front may have existed as a structural and lithologic discontinuity since Precambrian time.

AREA WEST OF THE GREEN AND COLORADO RIVERS

[Pls. 1 and 2]

Several prominent positive magnetic anomalies dominate the area west of the Green and Colorado Rivers, between the rivers and the San Rafael Swell. One, near Iron Wash and Saucer Basin (M18), is an apparent southeastward extension of a positive anomaly (M30) on the San Rafael Swell. It is almost on trend with the prominent pair of anomalies (M2, M3) near Upheaval Dome and Grays Pasture, interpreted to be caused by mafic Precambrian intrusions (Joesting and others, 1966, p. C12). Both highs are well north of the axis of the Nequoia arch. A small positive anomaly (M19) near Keg Knoll may connect the two groups of anomalies. If the two groups of anomalies are related and if they are caused by mafic rocks, it would appear that a continuous line of mafic Precambrian(?) intrusions extends from the Colorado River into the San Rafael Swell. Other prominent magnetic highs, one just southeast of Temple Wash (M20) and another near Big Wild Horse Mesa (M21), are similar in amplitude and configuration and may also be caused by mafic intrusions. Still another large high (M22) in the region near Robbers Roost Canyon and the Dirty Devil River, bordered on the south by a zone of steepened magnetic gradient (M23), may be caused by an intermediate to mafic body. These anomalies—except the one near Big Wild Horse Mesa, for which no gravity data are available — are associated with small positive residual gravity anomalies (pl. 1) that suggest dioritic or even more mafic rocks.

A positive magnetic anomaly (M99) southwest of the Green River has no gravitational counterpart and must be caused by basement rocks of moderate magnetization and relatively low density.

A very large magnetic low (M24) east of the Henry Mountains apparently is a polarization low associated with the magnetic high (M25) northwest of Hite, but it may also be caused by reversed remanent magnetization of the rocks.

Elsewhere in the region west of the Green and Colorado Rivers, the anomalies indicate low to moderate magnetization of the basement. Conspicuous elements of the map are elongate zones of steepened magnetic gradients that trend nearly east, especially the one extending from the Robbers Roost area to South Caineville Mesa (M23). Numerous such zones have been detected elsewhere in the Western United States (Zietz and others, 1969), and they represent a fundamental fracture pattern in the basement rocks. Locally, some Laramide faults trend east across the crest of the San Rafael Swell (Baker, 1946; Gilluly, 1929) and may represent rejuvenations of parts of a regional basement-fracture system.

SAN RAFAEL SWELL

[Pls. 1 and 2]

Only a few gravity traverses extended into the San Rafael Swell. Gravity relief across the Reef monocline, bordering the San Rafael Swell, is about 10 mgal. Well data indicate that relief of the Precambrian surface from the foot of Reef monocline to the crest of the San Rafael Swell is about 2,000–5,000 feet. The gravitational effect of a semi-infinite slab, 5,000 feet thick and having a density contrast of 0.2 g/cm^3, is about 6.4 mgal. If the density contrast is 0.3 g/cm^3, the gravitational effect is about 9.6 mgal. Thus, the observed gravity anomaly and the theoretical anomaly are in reasonable agreement, if the density of Precambrian rocks ranges from 2.7 to 2.75 g/cm^3 and the density of surficial sedimentary rocks ranges from 2.45 to 2.55 g/cm^3. Cuttings of Precambrian rocks from deep wells on the crest of the uplift are of granitic rocks, and densities on the order of 2.7 g/cm^3 are expected.

Over most of the San Rafael Swell, a series of ovoid magnetic highs (M26–M31) is the dominant pattern. These highs indicate that Precambrian rocks of moderate to strong magnetization coincide with the structural high over most of the swell. Southeast of the Reef monocline, anomaly amplitudes diminish somewhat, and the pattern is less heterogeneous. This suggests that the monocline may reflect a discontinuity in basement lithology and structure, analogous to that which is inferred to exist along the southwest flank of the Uncompahgre uplift.

In the northern part of the San Rafael Swell — in the extreme northwest corner of the surveyed area — the anomalies (M32–M34) are negative or are of low amplitude and gentle gradient, which is indicative of weak to moderately magnetic rocks.

The few drill holes on the San Rafael Swell that reached Precambrian basement penetrated fine- to medium-grained granites (pl. 3). Most of these holes were located on the lower amplitude anomalies or on the flanks of the higher amplitude anomalies, so it cannot be certain that the granites cause the larger magnetic anomalies.

MONUMENT UPLIFT

[Pls. 1, 2, and 3]

The gravity pattern over Monument uplift is mainly one of large closed highs and lows which, in general, are not related to small subsidiary folds on the crest of the uplift (pl. 1). Salt is relatively thin over the uplift, and it increases in thickness gradually from thin or absent at the south end to about 1,000–1,500 feet at the north end (Wengerd, 1958, fig. 14). Thus, local salt thickening cannot give rise to lows of −15 mgal, such as that on the Grand Gulch Plateau (G27). The well data indicate that most of the local anomalies over the uplift are related primarily to density contrasts within the Precambrian basement.

Gravity anomaly values are 10–20 mgal higher over the uplift than over immediately adjacent parts of the Blanding basin. Structural relief from the axis of Blanding basin to the crest of the uplift ranges from 5,000 to 6,500 feet. Calculations show that the gravity anomaly of a semi-infinite sheet, 6,000 feet thick, density contrast 0.2 g/cm^3, is 7.7 mgal; if the density contrast is 0.3 g/cm^3, the anomaly is 11.5 mgal.

Large gravity highs of 20 mgal or more are present near Monument Valley, between Kayenta, Ariz., and the Utah-Arizona State line (G28), and over Raplee anticline and Mexican Hat syncline (G29). These large triangular highs only partly reflect surficial structure (O'Sullivan, 1965, p. 92–102). For the most part, modeling shows that they represent irregular blocks of dense (2.9–3.0 g/cm^3?) Precambrian basement rocks. The large ovoid low of −15 mgal centered over the Grand Gulch Plateau on Cedar Mesa (G27) is evidently related to a low density mass (2.6 g/cm^3?) within the Precambrian basement. The small high of 10 mgal on Elk Ridge (G30) is related mainly to moderately dense basement rocks, although the local structural high at Elk Ridge contributes a small amount of the anomaly.

Over the Monument uplift the magnetic pattern is heterogeneous and is made up of a series of large ovoid highs and lows (pl. 2). Anomaly amplitudes are somewhat greater there than in the Blanding basin, to the east, and the Henry basin, to the west. The heterogeneous magnetic pattern over the west dip slope of the uplift is virtually the same as that over the Henry basin, but in the Blanding basin fewer magnetic highs are present.

Conspicuous magnetic highs are found near Gunsight Butte (M35), at Beef Basin (M36), and Dark Canyon (M37), where there also is a gravity high (G30); at Fish Creek (M38), Slickhorn Canyon (M39), Lime Ridge (M40), and near Mexican Hat, Utah (M41), where there is a large gravity high (G29); and at West Gypsum Creek (M101) and near Tyende Mesa, Ariz. (M42), near the structurally highest parts of Monument uplift. Where gravity highs are absent, the basement rocks must be of low density. The magnetic and gravity highs are caused by mafic rocks, but whether they are metamorphosed is unknown. A well drilled along the San Juan River near Mexican Hat, on the flanks of the magnetic high (M41), bottomed in "schist," which may or may not cause the prominent high just to the south. A few miles farther south, another basement well bottomed in "schist" beneath the magnetic high (M41). Along the crest of the uplift, a series of prominent magnetic lows is found near Woodenshoe Buttes (M103), Butts Canyon (M43), and near the south margin of the Grand Gulch Plateau, Utah (M44), locally associated with a prominent gravity low (G27), and near Mystery Valley and Monument Valley, Ariz. (M45). Such magnetic lows at structurally high positions along the uplift clearly indicate basement rock masses of low or reversed magnetization. Local anticlines and synclines superimposed on the crestal region of the uplift show little if any correlation with the positions of these magnetic anomalies. This fact emphasizes the intrabasement origin of the magnetic anomalies and the concept that development of these smaller Laramide folds was not greatly influenced by contacts between the basement rocks of different magnetization.

Some magnetic anomalies extend from the crest or eastern front of the Monument uplift across Comb Ridge monocline, where their amplitudes diminish greatly. Most noteworthy is the magnetic high that extends from Lime Ridge on the uplift (M40) to Cottonwood Wash (M46) in the margin of the Blanding basin. Other anomalies that cross Comb Ridge include a magnetic high (M47) that extends east-southeast from the San Juan River toward Boundary Butte (M48) and another that extends from Spearhead Mesa (M101) southeast across Greasewood Flat, near Dinnehotso, Ariz. (M49). But elsewhere along Comb Ridge, most of the magnetic anomalies seem to terminate at the monocline. These relationships indicate that the present site of Comb Ridge monocline was a zone of structural discontinuity during the Precambrian which was rejuvenated during the Laramide. Perhaps the rock masses that cause the anomalies crossing the monocline are of Precambrian age but younger than the main episode of Precambrian deformation that established the line of discontinuity under Comb Ridge.

AREA WEST OF THE MONUMENT UPLIFT

[Pls. 1 and 2]

West of the Monument uplift, magnetic highs (M50, M51) are found over the Circle Cliffs uplift, whose east boundary is the Waterpocket fold. Near

Oyster Shell Reef (Tps. 33 and 34 S., R. 8 E., just west of mapped area) and Swap Mesa, a magnetic low (M52) crosses the monocline; this low extends as an arcuate feature across the Cane Spring Desert. The highs are similar to those over the San Rafael Swell and suggest moderate to strongly magnetic rocks within the Precambrian basement.

Farther east, a prominent gravity high (G31) trends northwest, parallel to White Canyon, but only locally does it coincide with positive magnetic anomalies (M53, M54). Several sharp negative magnetic anomalies occur along the trend of the gravity high (M55, M56); thus, the basement, though relatively dense, is magnetically variable. Such relations may be analogous to those on the Uncompahgre Plateau, where amphibolites and gneissic granodiorite are dense but almost nonmagnetic (Case, 1966, p. 1431–1433).

One of the largest magnetic anomalies in a structural basin is that northeast of Mount Pennell and Mount Hillers (M25), near Trachyte Ranch. This high, in a deep part of the Henry basin, must be caused by a relatively magnetic rock mass. Whether it is of Precambrian age or whether it is related to the much younger Henry Mountains intrusions is unknown, but lack of deformation of the Mesozoic sedimentary rocks at the site of the anomaly suggests that the anomaly is within the Precambrian basement. The magnetic anomaly is located to the south of a positive gravity anomaly (G6).

Moderately magnetic rocks are indicated by the highs at Hite (M57), Goodhope Mesa (M58), and the area near the mouth of Lake Canyon near the Colorado River (M59). Farther to the northeast and east, highs at Lean-to Point (M60), near Burnt Spring (M61), Mikes Mesa (M62) area, and Nokai Dome (M63) are, likewise, all caused by moderately magnetized rocks. Areas of weak magnetization and locally low density are indicated near Woodenshoe Canyon (M102, G32), just north of Blue Canyon (M55), and near Mancos Mesa (M64). Other areas of weak magnetization are found at Nokai Mesa (M65) and southeast of Navajo Mountain (M66).

Many small gravity and magnetic anomalies not specifically described are scattered throughout the area west of the crest of Monument uplift.

AREA EAST OF THE MONUMENT UPLIFT

[Pls. 1 and 2]

In the area east of the Monument uplift, one of the most impressive magnetic anomalies is the high of more than 1,000 gammas (M67) that extends south from the Abajo Mountains to Blanding. This high is associated with a small residual gravity high (G33) and must be caused by a moderately dense and strongly magnetic rock mass, such as a diorite or gabbro.

An arcuate zone of magnetic highs that extends along Montezuma Creek and McElmo Creek (M68) in the deep part of the Blanding basin correlates approximately with low-amplitude gravity highs (G34), again indicative of moderately dense and magnetic rocks, perhaps dioritic.

The large-amplitude gravity (G35) and magnetic high (M48), just east of Boundary Butte, at the south edge of the area, is mostly caused by the dense and magnetic basement; amplitudes of the anomalies are far too large to be caused by the basement relief of Boundary Butte anticline and do not correlate positionally with the axis of the anticline. The magnetic (M69) and gravity (G36) highs that extend northeastward from Boundary Butte, near White Mesa, may represent an extension or lobe of this rock mass.

Magnetic highs northeast of Monticello (M70) and near Coal Bed Canyon (M71) correlate with moderate positive gravity noses (G37, G38), and a circular magnetic high (M72) near the head of Cross Canyon also correlates with a positive gravity nose (G39). Thus, the basement rocks are inferred to be moderately magnetic and dense (pl. 3), and perhaps dioritic.

In contrast, the large triangular magnetic high (M73) near Egnar, Colo., is in the region of a gravity low (G40). This gravity low may be caused by local salt thickening or it may be caused by low-density basement rocks such as granite.

Conspicuous gravity (G41) and magnetic (M74) lows that coincide in the area east and south of Blanding are probably caused by basement rocks of very low magnetization and density, such as granites or Precambrian sedimentary rocks. The flanks of these lows are locally bordered by elongate steep linear gradients (G42, G43, M75), trending northeast, which suggest shear zones in the basement (Case and Joesting, 1961). The dominant gravity anomaly is a huge low (G41) of –15 to –20 mgal whose axis trends northeast from south of Blanding to Eastland. Well data indicate that this low cannot be caused by basement relief or by salt thickening; therefore, it must be caused by a block of Precambrian rocks of low density (Case and Joesting, 1961), such as granite or a thick quartzite sequence.

In the extreme eastern part of the area, where magnetic surveys were flown but gravity surveys were not conducted, conspicuous magnetic highs are found between Dove Creek and the head of Yellowjacket Canyon (M76), just east of Sleeping Ute

Mountain (M77), and to the south, near Chimney Rock Draw (M78). Elsewhere in the area east of the Monument uplift, the magnetic anomalies are of low amplitude, indicating weak to moderate magnetization of the basement rocks.

Although most zones of steepened magnetic gradient trend northeastward, one prominent zone trends northwest, from near Cortez, Colo., to the Abajo Mountains (M78), and one trends westward from near Cortez into Utah, north of Hovenweep National Monument (M79).

Other small gravity highs and lows in the Blanding basin are not readily correlated with surficial structure and are probably caused by variations in salt thickness and by small intrabasement density contrasts. The series of small closed gravity lows between Comb Ridge and the Carrizo Mountains (G44, G45, G46) evidently indicates a rather uniform basement of low average density, granitic or quartzose rocks. Similarly, the lows east and southeast of the Carrizo Mountains (G47, G48) are partly intrabasement in origin, as they have no obvious relationship to surficial structure, except that they occur in the San Juan Basin.

DEFIANCE UPLIFT

[Pls. 1 and 2]

At the north end of the Defiance uplift, near the Arizona–New Mexico line, a large gravity high of 15 mgal (G49) trends northeast across the Laramide structural trends of Defiance monocline. Lack of correspondence between the gravity high and surficial structure indicates that the source of the anomaly is probably a dense rock mass within the Precambrian basement.

GEOPHYSICAL ANOMALIES OVER THE LACCOLITHIC MOUNTAINS

[Pls. 1 and 2]

Magnetic anomalies over the laccolithic mountains are of high amplitude and steep gradient, in keeping with positions of the igneous rocks at or near the ground surface and only slightly below the flight level of the aircraft. Positional correlation of the magnetic highs with the outcropping main stocks and laccoliths which form the peaks of the mountains is generally good to fair, especially as these igneous masses also tend to form topographic highs.

The gravity anomalies over the igneous intrusions in the various mountain groups, in contrast, are particularly difficult to isolate because of the influence of gravity gradients associated with other geologic features, and because of the large errors inherent in terrain corrections in mountainous regions.

LA SAL MOUNTAINS

[Pls. 1 and 2]

Magnetic anomalies over the La Sal Mountains group have been analyzed more completely than those near the other mountain groups (Case and others, 1963, p. 108–114). Briefly, the high-gradient anomalies closely reflect the areal pattern of the igneous intrusions. Highs are associated with Mount Tomasaki and Haystack Mountain in the north group (M80); with Mounts Mellenthin, Tukuhnikivatz, and Peale in the middle group (M81), and with South Mountain (M82). No discrete high was recorded near Manns Peak in the north group, but a broad high was recorded over the lower ground about a mile west, apparently because the rocks near Manns Peak are hydrothermally altered (Hunt, 1958, p. 335) and, hence, are less magnetic than the rocks farther west. Computations of magnetic models of North Mountain suggest that the anomaly can be accounted for by a floored laccolithic mass, 2,000–3,000 feet thick, if the susceptibility contrast is about 2×10^{-3} emu. At South Mountain, the anomaly can be approximately reproduced by a mass 4,000–5,000 feet thick having the same contrast. It was inferred from zones of steepened gravity gradient that the north group was apparently emplaced near the intersection of northeast- and northwest-trending zones of basement weakness (Case and others, 1963, p. 114).

The gravity anomaly of the igneous intrusions in the La Sal Mountains is obscured by anomalies related to salt thickening and to intrabasement density contrasts. However, the residual anomaly from Two-mile Creek to the middle group is about 6 mgal (G50), in line with the probable density contrast of 0.1 g/cm^3 (igneous intrusions 2.6 g/cm^3, adjacent sedimentary rocks 2.5 g/cm^3). The theoretical anomaly associated with intrusions at North Mountain is about 4 mgal, if the laccolithic mass is floored at an elevation of about 8,000 feet above sea level, and if the density contrast is 0.1 g/cm^3 (Case and others, 1963, p. 112–113).

HENRY MOUNTAINS

[Pl. 2]

An elongate magnetic high (M83) has been contoured over the northern part of Mount Ellen, eastward to Bull Mountain in the northern part of the Henry Mountains group. Inasmuch as several laccoliths occur within this elongate high, it seems likely that this magnetic high is the result of the manner of contouring, and not the result of a single intrusive mass. Local highs were delineated over the main Mount Ellen mass (M84), over the North Spur intrusion, and over the southern shoulder

(M85) of the Mount Ellen mass, correlative with the Mount Ellen stock (Hunt, 1953, p. 91–93, 107). Farther to the south, prominent ovoid highs are found over Mount Pennell (M86) and Mount Hillers (M87), each of which has a central stock; still farther south, positive anomalies center on Mount Holmes (M88) and Mount Ellsworth (M90). No significant anomalies were found that would suggest large buried Tertiary intrusive centers.

The intrusions in the Henry Mountains group occur generally along a northwest-trending zone (M89) of steepened magnetic gradient that may indicate a basement-fracture zone. Mount Holmes and Mount Ellsworth are near the intersection of the northwest-trending zone and a similar north-trending zone (M100). Hunt (1953, p. 143) suggested that the intrusions were controlled either by joint sets (which trend northwest and northeast) or by a more fundamental structure that is reflected by the joints. The magnetic map shows a northeast-trending line of magnetic discontinuity (M91) that projects through Mount Holmes and Mount Ellsworth and that is the site of surficial faults (Hunt, 1953, p. 143). Thus, it appears from the magnetic data that three basement fractures may intersect near Mount Holmes and Mount Ellsworth.

ABAJO MOUNTAINS

[Pls. 1 and 2]

Magnetic anomalies (M93) correlate moderately well with laccoliths or stocks of the Abajo Mountains. Locations of igneous bodies discussed in this section are shown on plate 1 of Witkind (1964). A broad high (M92) centers over Shay Mountain, which is underlain by an inferred concealed stock (Witkind, 1964, p. 47) around which small laccoliths are exposed. A prominent high coincides with the North and South Robertson Pasture laccoliths and a small high with the Horsehead laccolith. Other highs correlate approximately with the Gold Queen, Jackson Ridge, and South Peak laccoliths. To the west, a high is present over the West Mountain stock and Mount Linnaeus laccolith, and a prominent sharp high over the Scrub Oak and Prospect laccoliths, near Shay graben. An isolated magnetic high along the boundary between Rs. 22 and 23 E. in T. 33 S. correlates approximately with the Spring Creek anticline, which was interpreted by Witkind (1964, p. 59) to be underlain by a laccolith. The magnetic data thus confirm Witkind's interpretation.

The Abajo Mountains lie at the intersection of linear zones (M78, M94) of northwest- and northeast-trending steepened magnetic gradients, again indicating that basement fractures have localized the intrusions.

Isolation of a residual gravity anomaly over the Abajo Mountains is also difficult because of complex regional gravity gradients. Depending on the regional gradient assumed, the residual anomaly over the main mass of the Abajo Mountains is about 8–12 mgal (G51), and over Shay Mountain (G52), about 4–6 mgal. However, the crest of the gravity high near Shay Mountain is not centered on the mountain proper but in a canyon to the northeast, suggesting that part or all of the anomaly may be related to a deeper source than the known igneous intrusions at Shay Mountain proper.

In any event, the gravity anomalies associated with the Abajo Mountains are somewhat greater in amplitude than one might expect from the volume of exposed igneous rocks and from the probable density contrasts (0.1–0.2 g/cm^3). Therefore, it is very likely that a rather large igneous body is concealed at depth, or that the laccoliths were emplaced at a site which is underlain by dense Precambrian rocks.

SLEEPING UTE MOUNTAIN

[Pls. 1 and 2]

Correlation of magnetic highs (M95) and the main intrusive centers of Sleeping Ute Mountain is very poor. For example, a magnetic low is present over the north flank of Ute Peak, which is the site of a stock bysmalith, and over the Mable Mountain bysmalith (Ekren and Houser, 1965, pl. 1, p. 55) which is thoroughly altered and mineralized with pyrite. A magnetic high is present over the laccoliths just south of Ute Peak, and others are present over the laccoliths of the western part of the mountain group. Only a small positive nose was detected near Hermano Peak. These relationships indicate lowering of magnetization by alteration of magnetite or, in some localities, possible reversed magnetization of the intrusions.

Sleeping Ute Mountain lies near the intersection of two zones of steepened magnetic gradient — one trending east (M79), the other trending north to northwest (M96). Deep-seated structures seem indicated at Sleeping Ute Mountain (Ekren and Houser, 1965, p. 52), but evidence for them is less compelling than it is for such structures at most of the other laccolithic groups. A zone of steepened gravity gradient trends east (G53), coinciding with the steep east-trending magnetic gradient. This is apparently a zone of rather abrupt northward thickening of the Paradox salt, which suggests the possibility of a presalt fault or hinge line (Ekren and Houser, 1965, p. 52). An east-trending fracture in Precambrian rocks is postulated to have been rejuvenated during late Paleozoic time, and ultimately served as a partial control for localization of the laccoliths.

The residual gravity anomaly (G54) over Sleeping Ute Mountain is evidently about 6 mgal, although the anomaly is obscured by the strong east-trending regional gradient related to northward thickening of the Paradox salt and to deepening of the basement.

CARRIZO MOUNTAINS

Parts of the Carrizo Mountains and vicinity have been mapped aeromagnetically by Frischknecht, Petrafeso, and others (1963a, b, c, d, e), but we did not attempt to interpret these maps for the present report.

A gravity high of 4–8 mgal was detected over the Carrizo Mountains. The large gravity anomalies that dominate the Carrizo Mountains and vicinity and the Defiance uplift are principally the expression of rock units of different densities within the underlying Precambrian basement, according to the gravity-data interpretation by Plouff (1958).

SMALL INTRUSIONS

A few very small sharp anomalies (M97) are found over the mafic intrusions and dikes southeast of Paradox Valley, near the head of Dry Creek basin (Williams, P. L., 1964) and near Glade Mountain (M98).

DEEP-SEATED STRUCTURAL BOUNDARIES INFERRED FROM GRAVITY DATA

Some inferred causes of zones of steepened gravity gradient related to deep-seated structural zones in pre-Paradox rocks may be summarized as follows:

1. The zone (G3) that extends eastward from Mineral Point to Spanish Valley is caused by a combination of northward salt thickening, deepening of the basement to the north, and less dense Precambrian basement to the north. This feature may have served as a partial control for the position of the southeastern part of Spanish Valley salt anticline.
2. The zone (G4) that extends northeast from Spanish Valley to the north flank of the northern group of the La Sal Mountains is related to a transverse, northeast-trending, deep-seated zone that has thicker salt, deeper basement, and less dense Precambrian rocks on its northwest side than on its southeast side. A gravity high on the same trend as the zone of steepened gradient extends to the Uncompahgre front near Gateway and may represent a transverse barrier in the deep Paradox basin.
3. The northwest-trending zone (G5) along the northern group of the La Sal Mountains and along the southwest flank of Paradox Valley is caused by a deep-seated fault or warp along the southwest side of Paradox Valley salt anticline. Between Wray Mesa and the center of Paradox Valley the presalt surface is displaced by 5,000 feet or more, and the downthrown side is to the northeast.
4. The huge gravity low (G41) in the Blanding basin, southeast of Monticello, is bordered by relatively straight contours. The high (G29) over Raplee anticline and Mexican Hat syncline is, likewise, bordered on its northeast side by straight gravity contours. These zones of linear steepened gravity gradient have been interpreted as deep-seated faults in the Precambrian basement which trend northeast and which may represent transverse Precambrian shear zones of the type recognized in the Colorado mineral belt (Tweto and Sims, 1963).

BASEMENT POLYGONIZATION

Lithologic units of the Precambrian basement (pl. 3), as interpreted from analysis of the combined gravity anomaly and magnetic maps (pls. 1, 2), have boundaries that form a polygonal array or that are mostly ovoid to circular. Because most of the geophysical anomalies are observed at a level that is many thousands of feet above the sources of the anomalies, the anomalies themselves are smoothed and broadened in comparison to what they would be if observed immediately on top of the Precambrian basement. Thus, the zones of nearly straight, elongate steepened geophysical gradients would be even more nearly rectilinear if observed at a lower level. Where the gradients and geophysical discontinuities fall along lines, they clearly indicate faults in the basement; so, we may generalize that the basement pattern is one of fault blocks, which correspond to zones of nearly straight steepened gravity and magnetic gradients, and to intrusive bodies which range in composition from gabbroic to granitic and which correspond to circular, ovoid, and irregular gradients.

Isotopic ages suggest episodes of igneous intrusions on the Uncompahgre Plateau during the interval 1.7 to 1.4 b.y. (billion years) ago (Hedge and others, 1968; Mose and Bickford, 1969). The sedimentary sequence that ultimately was metamorphosed must have formed prior to 1.7 b.y. ago. If our inference is correct that units equivalent to those on the Uncompahgre Plateau extend across the central Colorado Plateau to the Grand Canyon area, then the bulk of the polygonal fracture pattern originated less than 1.7 b.y. ago, and probably after emplacement of plutons which range in age from

1.7 to 1.4 b.y. (See Giletti and Damon, 1961, and Wasserburg and Lanphere, 1965, for age data to the southwest in Arizona.) Igneous activity was apparently absent on the Uncompahgre Plateau at approximately 1 b.y. ago, when it was so significant to the east in Colorado, New Mexico, and Texas (Goldich and others, 1966, fig. 6). Whether the polygonization of the basement in the Colorado Plateau was contemporaneous with the widespread igneous activity to the east, or whether it preceded or followed that igneous activity, is unknown. It is tempting to correlate at least part of the polygonization with the two episodes of deformation in the Grand Canyon area — the first corresponding to folding and metamorphism of the Vishnu Schist and emplacement of plutonic rocks (1.7 to 1.4 b.y. ago) and the second corresponding to block faulting that occurred after deposition of the Grand Canyon Series, possibly less than 1.2 b.y. ago (Silver, 1960).

REGIONAL CRUSTAL RELATIONS

Crustal thickness between Chinle, Ariz., and Hanksville, Utah, is about 40 km, as determined on the basis of seismic refraction lines (Warren, 1968). Crustal thickness increases eastward to about 50 km near Climax, Colo., in the Rocky Mountains (Jackson and Pakiser, 1965). Mean regional Bouguer anomalies decrease from about -200 mgal (for a reduction density of 2.67 g/cm^3) in the central Colorado Plateau to about -250 mgal near Climax, and this eastward decrease is consistent with 10 km of eastward crustal thickening. These regional crustal relations have little influence on the interpretations of the gravity and magnetic data presented in this report, as most of the anomalies arise from lithologic or structural variations within the upper few kilometers of the Precambrian complex or in the Paleozoic and Mesozoic sedimentary sequence.

Polygonization of the Precambrian basement, described in the preceding section, seems consistent with the model presented by Archambeau, Flinn, and Lambert (1969) that the Rocky Mountains and the Colorado Plateaus province are underlain by low-velocity zones in the upper mantle, capped by a high-velocity [rigid] lid zone, in contrast to the thin or absent "lid" zone of the Basin and Range province.

SUMMARY

Precambrian basement. — Analysis of the gravity and magnetic maps clearly indicates the extreme heterogeneity of the Precambrian basement. Evidence has been found from outcrops on the Uncompahgre Plateau, from drill holes, and from inclusions in younger igneous rocks that the basement over much of the area is a metamorphic complex of gneisses and schist intruded by a variety of granitic rocks and locally by mafic to ultramafic bodies. Metamorphic rocks are of generally high grade (almandine-amphibolite facies) except in the extreme southeast, where quartzites have been penetrated by deep drill holes near the Defiance uplift and in the southwest, where rocks correlated with the argillites and quartzites of the Grand Canyon Series have been penetrated by drill holes.

Patterns of steepened magnetic and gravity gradients are interpreted to represent lithologic contacts. Many contacts between rock units are crudely oval or circular, indicative of intrusive contacts, or they are curved, possibly indicating a folded contact in a metamorphic sequence. A surprising number of contacts are relatively straight for many miles, suggestive of faults or shear zones. These lineaments tend to fall in four groups — northwest, northeast, north, and east — and may represent a fundamental fracture pattern of the basement rocks. The northeast trend may be part of a larger regional pattern en echelon with shear zones of the Colorado mineral belt and Grand Canyon area. The east trend may form part of an en echelon belt that trends across much of the Western United States from California into the High Plains of Colorado (Zietz and others, 1969).

Paleozoic structures. — Drill data indicate much minor structural movement of the central Colorado Plateau prior to the formation of the ancestral Uncompahgre highland and Paradox basin. Only a few of these structural lines can be deduced with assurance from the gravity and magnetic data. These are the presalt fault along the southwest flank of Paradox Valley salt anticline, one along the southwest flank of Gypsum Valley anticline, and one along a segment of Moab Valley—Spanish Valley anticline. Drill data indicate a presalt structural high, possibly fault bordered, under the southwest flank of Lisbon Valley. All these presalt faults trend northwest. A prominent northeast ridge, possibly fault bordered, parallels the Colorado River from the northwest nose of Monument uplift to Moab Valley. Another geophysical lineament suggestive of a basement fault trends northeast near the La Sal Mountains and projects into the Uncompahgre uplift, where magnetic anomalies show a pronounced offset.

The deep part of the Paradox basin is defined by a regional gravity low, and the position of the buried Uncompahgre front is defined by both gravity and magnetic anomalies, especially steepened gradients.

Prominent gravity lows define the salt anticlines, and analysis of the anomalies indicates that the amplitudes of the salt cores are from 2,000 to 11,000 feet. The greatest amplitudes are found for anticlines in the deepest part of the Paradox basin. The presence of two salt anticlines has been confirmed by gravity data — one at Pine Ridge and one at Tenmile Wash. Many small anticlines, such as Cane Creek anticline and Shafer dome, have little or no gravity expression.

Laccolithic intrusions. — The laccoliths of the central Colorado Plateau yield small, poorly defined positive gravity anomalies of about 5 mgal. Magnetic anomalies correlate well with most of the intrusive centers. Gravity and magnetic lineaments tend to intersect at most of the laccolithic groups, suggesting that basement fractures controlled the sites of final emplacement of magma.

Laramide structures. — General gravity and magnetic highs coincide with the monoclinal upwarps, as expected, but many of the anomalies attributable to different rock types in the Precambrian basement exceed and therefore mask whatever anomalies may be attributed to structure uplift. If all of the Laramide structures were flattened out, the resulting overall pattern of gravity and magnetic anomalies would be little affected.

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