Regional Geophysical Investigations in the La Sal Mountains Area Utah and Colorado

By J. E. CASE, H. R. JOESTING, *and* P. EDWARD BYERLY

GEOPHYSICAL FIELD INVESTIGATIONS

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REGIONAL GEOPHYSICAL INVESTIGATIONS IN THE LA SAL MOUNTAINS AREA, UTAH AND COLORADO

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ABSTRACT

Regional gravity and aeromagnetic surveys covering about 1,000 square miles have been made in the La Sal Mountains area of southeast Utah and southwest Colorado as part of a program of geophysical studies of the Colorado Plateau. Major geologic features are the laccolithic La Sal Mountains, and parts of the northwestward-trending salt anticlines at Castle, Fisher, Spanish, Sinbad, and Paradox Valleys, and at Pine Ridge.

Sedimentary rocks exposed in the area include marine beds of Pennsylvanian and Permian (?) age; continental beds of Permian, Triassic, Jurassic, and Early Cretaceous age; and marine beds of Late Cretaceous age. Marine beds of Mississippian, Devonian, and Cambrian age have been penetrated by deep wells. The densities of most of the sedimentary rocks range from 2.5 to 2.65 g per cm^3, but evaporites of Pennsylvanian age, which form the cores of the salt anticlines, have densities of about 2.2 to 2.3 g per cm^3.

The igneous intrusions comprising the three laccolithic groups of the La Sal Mountains are of latest Cretaceous or early to middle Tertiary age. The intrusive rocks are diorite porphyry, monzonite porphyry, and syenite porphyry. They have an average density of about 2.61 g per cm^3 and an average magnetic susceptibility of about 0.002 cgs units, as determined by sampling.

The salt anticlines and the laccolithic intrusions at North and South Montains trend northwestward, parallel to the structural front of the Uncompahgre uplift and to the axis of Sagers Wash syncline. In these areas the igneous rocks were injected along the strike of older salt anticlines. Steepened regional gravity and magnetic gradients along Paradox Valley salt anticline and North Mountain are apparently related to northwestward-trending basement faults or warps, so that deep-seated structural control is indicated for the positions of the salt anticline and the igneous intrusions.

Other prominent zones of steepened regional gravity gradients, which coincide in trend with magnetic contours, are also apparently related to structural and lithologic changes in the Precambrian basement rocks. These indicated basement structural zones trend east-west between South Mountain and Kane Springs Canyon and northeast between Pack Creek and North Mountain.

Basement rocks are probably shallower, and possibly more dense, south of and beneath the La Sal Mountains than at Polar Mesa and at Spanish, Fisher, and Sinbad Valleys. A broad zone of comparatively flat magnetic gradient extending beneath the La Sal Mountains indicates that the basement rocks are uniformly magnetized and are probably of low to moderate magnetization.

The salt anticlines of the area are left-laterally offset along a zone extending northeastward from Pack Creek past Polar Mesa. This zone of offset coincides with northeastward-trending gravity and magnetic contours, indicating that Pennsylvanian, or earlier, faulting of the Precambrian basement may have occurred. The igneous intrusions at North Mountain were emplaced near the intersection of the inferred northeastward-trending basement fault with the northwestward-trending basement fault which extends from Paradox Valley to North Mountain.

Amplitudes of the salt cores of the anticlines at Fisher and Castle Valleys are indicated by gravity minima to be about 10,000 and 7,000 feet, respectively. Thickened salt of Castle Valley anticline apparently extends beneath the northwest laccoliths of North Mountain and may be continuous at depth with thickened salt of the Paradox Valley anticline. Thickened salt may also extend partly beneath South Mountain, according to available geologic and gravity evidence.

High-gradient magnetic anomalies closely reflect the areal pattern of the igneous intrusions of the mountains. Analysis of the anomaly at North Mountain indicates that the average aggregate thickness of the laccoliths, exclusive of a central feeder stock, is about 2,000 to 2,500 feet. At South Mountain the maximum thickness of the laccoliths may be 4,000 to 5,000 feet. There is no magnetic indication of a parent body from which the laccolithic complex was derived, therefore, any such body probably lies at comparatively great depth.

INTRODUCTION

Regional gravity and aeromagnetic surveys have been made over the La Sal Mountains and the adjacent canyon lands of southeast Utah and southwest Colorado (fig. 33) as part of a program of geophysical studies of the central Colorado Plateau. The area is near the deeper part of the Paradox basin of Pennsylvanian age and is just southwest of the Uncompahgre uplift, a rejuvenated part of the ancestral Rocky Mountains.

These surveys are an extension of those made east of the La Sal Mountains in the Uravan area (Joesting and Byerly, 1956, 1958), south of the La Sal Mountains in the Lisbon Valley area (Byerly and Joesting, 1959), and

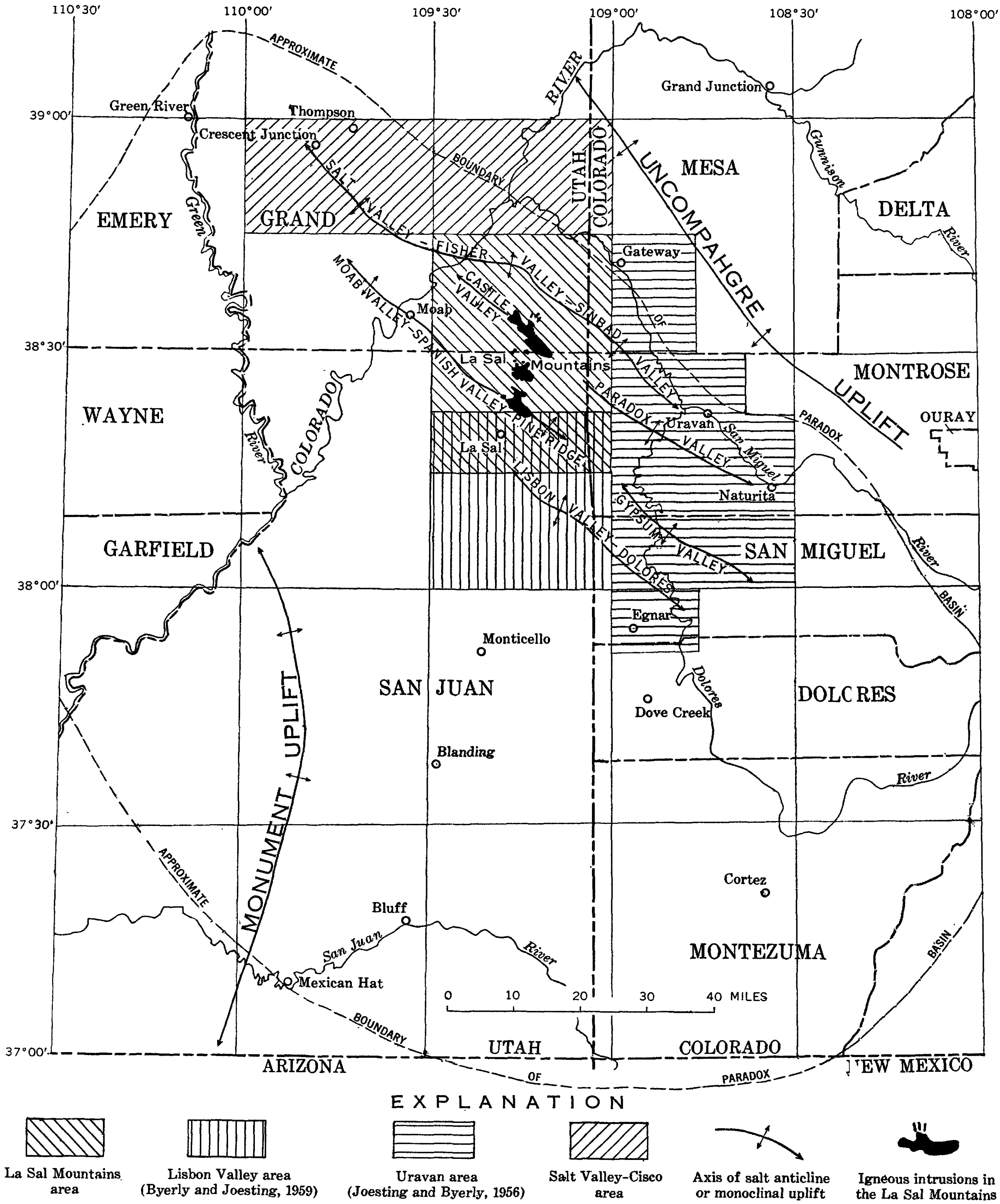

Figure 33.—Index map showing location of the La Sal Mountains area.

north of the La Sal Mountains in the Salt Valley–Cisco area (Joesting and Case, 1962). They were made to gain information on the structure of the buried Precambrian rocks, on the shapes of the salt anticlines and laccoliths and their relation to deep-seated structure, and on the relation of buried structures to the occurrence of uranium and oil.

We acknowledge with thanks the advice and interest of many geologists of the U.S. Geological Survey and the U.S. Atomic Energy Commission. We are particularly indebted to C. B. Hunt, E. M. Shoemaker, G. W. Weir, P. L. Williams, W. P. Puffett, and W. D. Carter for many helpful suggestions on interpretation of results. C. B. Hunt of the U.S. Geological Survey provided numerous specimens of igneous rocks from the La Sal Mountains for measurement of densities and magnetic susceptibilities. G. S. Horne, W. K. Dyer, and H. H. Ingalls assisted on the gravity survey; R. B. Helmick, R. A. Barbour, and H. H. Smith assisted in compilation of the gravity data; and Roy Shuler assisted in theoretical computations based on the magnetic data. The aeromagnetic surveys were flown under the direction of J. L. Meuschke and R. W. Bromery, and compilation of the aeromagnetic map was supervised by W. J. Dempsey.

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GEOLOGY

Rocks exposed in the La Sal Mountains area range in age from Pennsylvanian to Recent (pl. 14). Principal rock units of geophysical significance are the buried Precambrian rocks and pre-Pennsylvanian sedimentary rocks; the Hermosa Formation of Pennsylvanian age, which includes the low-density Paradox Member; the Cutler Formation of Permian age; sedimentary rocks of Mesozoic and Cenozoic age; and igneous rocks of the laccolithic intrusions in the La Sal Mountains, which are of late Mesozoic or early to middle Tertiary age (table 1).

ROCKS OF PRECAMBRIAN AGE

Precambrian crystalline rocks are exposed in the core of the Uncompahgre uplift, east of the La Sal Mountains area (Shoemaker, 1956), but they are buried beneath 8,000 to 17,000 feet of sedimentary and igneous rocks within the area discussed in this report. Basement crystalline rocks have been penetrated in the Pure 1 Gateway (sec. 15, T. 15 S., R. 104 W., 6th principal meridian) near the Dolores River in the northeastern part of the area, where granite was found about 3,100 feet below sea level beneath a cover of 7,800 feet of arkose of possible Pennsylvanian and Permian(?) age (fig. 34). Precambrian rocks were penetrated at an elevation of 4,668 feet below sea level in the Shell 1 Wray Mesa Unit (sec. 21, T., 47 N., R. 19 W., New Mexico principal Meridian), southwest of Paradox Valley. Biotite granite was found in the Pure 2–A NW Lisbon (sec. 10, T. 30 S., R. 24 E., Salt Lake meridian), southwest of Lisbon Valley (fig. 1), at an elevation of about 2,670 feet below sea level. Configuration of the basement surface shown in figure 34 is discussed more fully on page 105.

Many inclusions are present in the igneous rocks of the La Sal Mountains. Waters and Hunt (*in* Hunt, 1958, p. 349–351) have found that some of the inclusions are unmodified granite, gneiss, and schist from the crystalline basement, and some are undoubtedly xenoliths of Paleozoic or Mesozoic sedimentary rocks. However, most of the inclusions are hornblendic in composition and were probably derived from preexisting amphibolites or related metamorphic rocks of the Precambrian basement.

From the lithology of the inclusions it may be inferred that the upper part of the Precambrian basement beneath the La Sal Mountains is granite, gneiss, and schist, whereas a high proportion of amphibolites or related rocks are present at greater depths within the basement. Broad low-gradient regional magnetic anomalies indicate that at least the upper part of the Precambrian basement is of low to moderate, comparatively uniform magnetization.

The density of the Precambrian rocks is unknown, but probably ranges from 2.60 to 3.07 g per cm^3, averaging about 2.71 g per cm^3. These are similar to densities obtained from surface samples in the Uncompahgre Plateau and adjoining regions (Joesting and Byerly, 1958, p. 4).

SEDIMENTARY ROCKS OF PRE-HERMOSA AGE

The oldest Paleozoic rocks exposed in the La Sal Mountains area are beds of the Hermosa Formation of Pennsylvanian age. Cambrian, Devonian, and Mississippian strata, and Pennsylvanian strata of pre-Hermosa age (Molas Formation) are present in the San Juan Mountains of Colorado and have been identified in deep wells south, east, and west of the La Sal Mountains. Cooper (1955, p. 59–65) has estimated that the total thickness of the pre-Pennsylvanian sedimentary rocks is about 1,000 feet in the eastern part of the Paradox basin and 2,500 feet in the western part. The Cities Service 1–B Government (sec. 34, T. 28 S., R. 22 E., Salt Lake meridian, fig. 34), southwest of the La Sal Mountains, bottomed in Devonian strata after drilling through about 900 feet of beds of pre-Pennsylvanian

TABLE 1.—*Generalized geologic column*

[Data from Carter, 1956; Cooper, 1955; Craig and Dickey, 1956; Hunt, 1958; E. M. Shoemaker, written communication, 1961; Stewart, 1956; G. W. Weir, written communication, 1961; and Wengerd and Strickland, 1954]

System	Group, formation, and member	Thickness (feet)	Description of rocks	Estimated or measured density in g per cm³	Estimated or measured magnetic susceptibility in cgs units
Quaternary and Tertiary.		0–1, 000?	Alluvium, talus, conglomerate, and glacial drift.	2. 2 –2. 4	Zero to low.
Tertiary or Cretaceous	Igneous rocks of the La Sal Mountains.		Diorite porphyry, monzonite porphyry, and syenite porphyry.	2. 61	0.0016–0.0021
Cretaceous	Mancos Shale	0–2, 500?	Shale, sandstone, and siltstone.		
	Dakota Sandstone, Burro Canyon Formation.	350?	Sandstone and siltstone.		
Jurassic	Morrison Formation	700	Shale, sandstone, and siltstone.	2. 3 –2. 5	Zero to low.
	San Rafael Group: Summerville Formation, Entrada Sandstone, Carmel Formation.	200?–500	Sandstone and siltstone.		
Jurassic and Triassic	Glen Canyon Group: Navajo Sandstone, Kayenta Formation, Wingate Sandstone.	600–900	Sandstone and siltstone.		
Triassic	Chinle Formation, Moenkopi Formation.	0–1, 700	Shale, siltstone, and sandstone.		
Permian	Cutler Formation	0–8, 000?	Arkosic conglomerate, arkosic sandstone, and shale.		
Permian(?) and Pennsylvanian.	Rico Formation	0–300?	Limestone, shale, and arkosic sandstone.	2. 58–2. 65	Do.
Pennsylvanian	Hermosa Formation: Upper member	0–5, 000?	Limestone, shale, and arkosic sandstone.		
	Hermosa Formation: Paradox Member	0–7, 000?	Salt, gypsum, black shale, and limestone.	2. 2 –2. 3	Do.
	Hermosa Formation: Limestone member	0–3, 000?	Limestone and shale		
	Molas Formation	0–50	Limestone and shale	2. 6 –2. 7	Do.
Pre-Pennsylvanian (Mississippian, Devonian, and Cambrian).		0–2, 000?	Limestone, shale, dolomite, and sandstone.		
Precambrian			Schist, gneiss, and granite.	2. 6 –3. 0?	Low to 0.003(?).

age. The Humble 1 Bridger (sec. 17, T. 27 S., R. 22 E., Salt Lake meridian), just southwest of Spanish Valley, bottomed in Cambrian strata after drilling through 930 feet of beds of pre-Hermosa age. South of the area, the Pure 2–A penetrated about 1,600 feet of Mississippian and older Paleozoic strata. Therefore, it is assumed that 1,000 to 2,000 feet of pre-Pennsylvanian strata is present in the La Sal Mountains area.

Well cuttings, cores, and outcrops of beds of pre-Hermosa age in adjacent areas are largely composed of limestone and quartzite. These rocks are probably about as dense as the average Precambrian rock, but their magnetic susceptibilities are very low. Therefore, they will be considered with the Precambrian basement in gravity interpretations, and with the overlying sedimentary rocks in magnetic interpretations.

SEDIMENTARY ROCKS OF LATE PENNSYLVANIAN AND PERMIAN AGE

The Hermosa Formation of Pennsylvania age comprises three members: a lower limestone member; the

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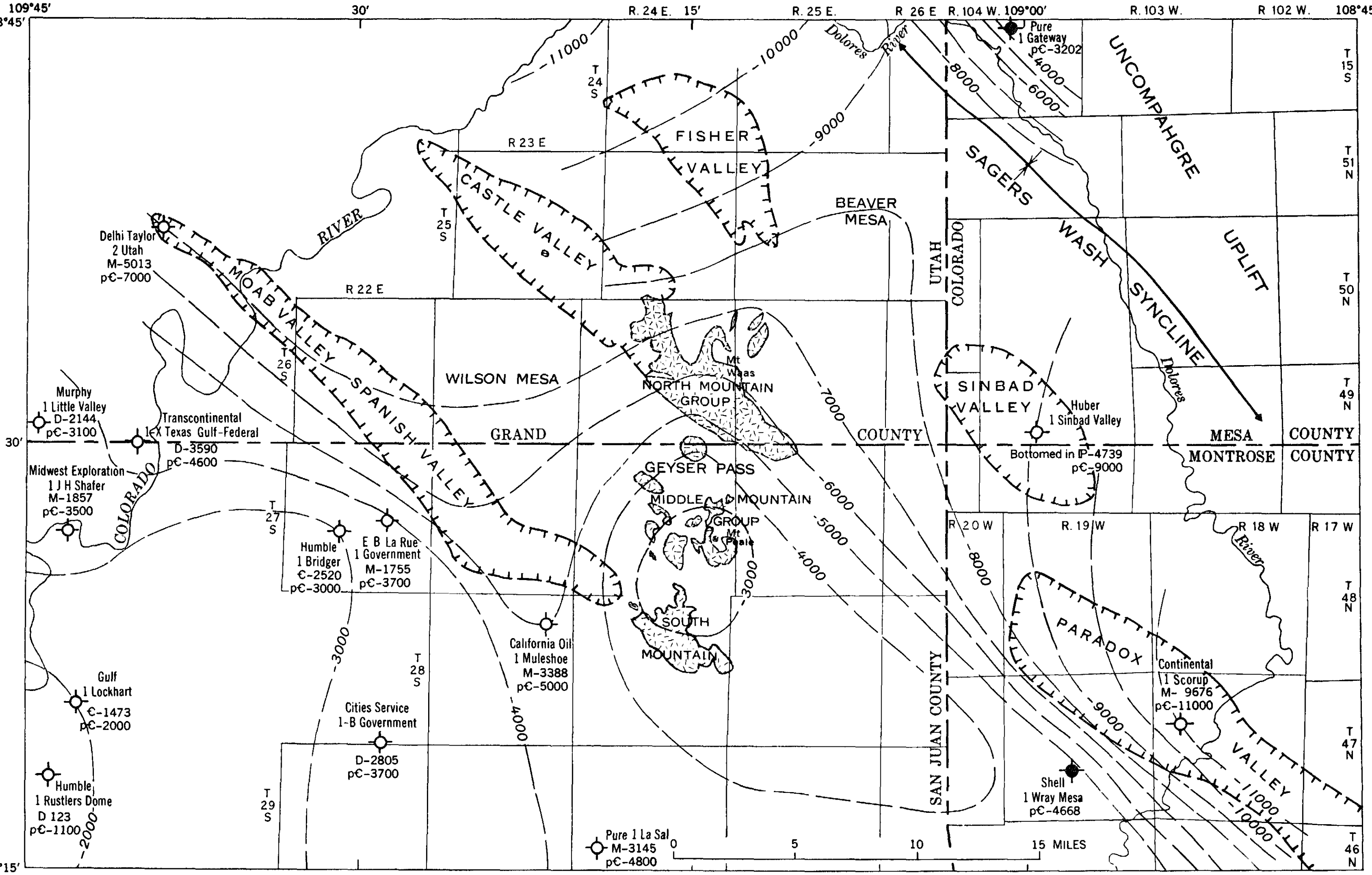

EXPLANATION

Tertiary igneous rocks

Axis of syncline, showing direction of plunge

— 4000 —

Form line showing inferred elevation, in feet, of the Precambrian surface

Contour interval 1000 feet. Datum is mean sea level

Approximate boundary of valley of major salt anticline

M-3388
p€-5000

Drill hole penetrating Pennsylvanian, P, Mississippian, M, Devonian, D, or Cambrian, €, strata, showing elevation, in feet, of top of series and estimated elevation of the Precambrian, p€, surface

p€-4668

Drill hole penetrating Precambrian rocks, showing elevation, in feet, of the Precambrian surface

FIGURE 34.—Inferred configuration of the Precambrian surface in the La Sal Mountains area and vicinity.

Paradox Member, a thick cyclical sequence of evaporites, black shale, sandstone, limestone, and locally, arkosic rocks; and an upper member which consists of marine limestone and shale, which grades to sandstone and conglomerate toward the northeast (Bass, 1944; Wengerd and Strickland, 1954). The maximum depositional thickness of the Paradox Member may be as much as 7,000 feet near Paradox Valley, according to Elston and Shoemaker (1960, p. 49–51). Wengerd and Strickland (1954, p. 2174) have estimated the thickness of the upper member, including coarse clastic parts adjacent to the Uncompahgre uplift, to be about 5,000 feet. In the Humble 1 Bridger the approximate thickness of the upper member is about 1,980 feet, of the evaporite series about 1,730 feet, and of the lower member about 146 feet. The Hubbard 1 Government (sec. 12, T. 24 S., R. 23 E., Salt Lake meridian), northeast of Onion Creek, bottomed in the Paradox Member after penetrating about 2,100 feet of the upper member and 170 feet of the Paradox Member (E. M. Shoemaker, written communication, 1961).

Beds of the Hermosa Formation are exposed near the crest of salt anticlines at Sinbad, Fisher, and Castle Valleys, where the leached gypsum caprock is prominent.

The Paradox Member is the most significant sedimentary unit of the area with respect to interpretation of the gravity data. The relatively low density of the evaporite series causes pronounced gravity minima where the salt forms the thickened cores of the salt anticlines. The density of halite is about 2.1 g per cm^3 (Birch and others, 1942, p. 10), but the Paradox Member includes denser clastic and nonclastic beds, and the percentage of clastic material within the member increases from southwest to northeast toward the Uncompahgre uplift. The average density of the salt interval thus increases from southwest to northeast (Shoemaker and others, 1958, p. 47–48; Elston and Shoemaker, 1960, p. 49–51). The average density of the Paradox Member in the core of the most easterly salt anticlines may be as high as 2.3 g per cm^3.

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. The thickness of the Rico Formation in the Hubbard 1 Government is about 300 feet, according to E. M. Shoemaker (written communication, 1961). The Rico Formation is locally exposed in Sinbad Valley. Nonfossiliferous limestone which may be in the Rico Formation is also exposed in the hogbacks flanking the North Mountain group of peaks and South Mountain.

The Cutler Formation of Permian age overlies the Rico Formation. The formation increases in thickness northeastward toward the Dolores River. More than 4,000 feet of arkosic beds were penetrated by the Hubbard 1 Government well, and, as previously noted, about 7,800 feet of arkosic material was penetrated by the Pure 1 Gateway. Formation boundaries could not be picked in the Pure 1 Gateway and some of the material may represent equivalents of the Hermosa and Rico Formations. The Cutler Formation is exposed along the Dolores River; in the cliffs at Sinbad, Fisher, Castle, and Spanish Valleys; in the hogbacks of the North Mountain group and at South Mountain; and along the Colorado River near Professor Creek.

In addition to the general northeastward thickening of the Cutler Formation, there are notable variations in thickness related to growth of the salt anticlines. There is stratigraphic and geophysical evidence that the Cutler Formation thins toward the crests of the salt anticlines and thickens in areas between the salt anticlines (Shoemaker and others, 1958, p. 48–55; Elston and Landis, 1960, p. B–261; Elston and Shoemaker, 1960, p. 53; Joesting and Byerly, 1958, p. 12, 15, 16).

The effective density of the Rico and Cutler Formations and the limestone of the Hermosa Formation is probably about 2.55 to 2.65 g per 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 per 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 per cm^3 (Joesting and Byerly, 1958, p. 5).

SEDIMENTARY ROCKS OF MESOZOIC AND CENOZOIC AGE

Mesozoic strata of the area are dominantly continental sandstone, shale, and conglomerate. However, the Mancos Shale of Late Cretaceous age is marine. Hunt (1958, p. 310) has estimated that about 3,500 feet of Mesozoic strata is present in the La Sal Mountains. The average density of Mesozoic rocks from the Wingate Sandstone of Triassic age to the Morrison Formation of Jurassic age was found to be about 2.5 g per cm^3, from gravity measurements at the top and bottom of the canyon of the San Miguel River near Uravan, Colo. (Joesting and Byerly, 1958, p. 7).

Deposits of alluvium, conglomerate, and windblown material of Cenozoic age are found in the valleys, on alluvial fans around the mountains, and on some of the mesas. Glacial deposits are widespread in the mountains (Hunt, 1958, p. 314). In general, the Cenozoic deposits are thin, but in the valleys along the breached crests of the salt anticlines the fill may be 1,000 feet thick (Hunt, 1958, p. 314). The density of much of the relatively porous fill probably does not differ appreciably from that of the underlying evaporates. The thin Cenozoic deposits have little effect on the gravity and magnetic interpretations.

Mesozoic and Cenozoic strata blanket much of the area and, considered together, are 4,000 to 5,000 feet thick, for which a density of 2.5 g per cm³ has been assumed. Gravity reductions, including terrain corrections, have been made using this density.

IGNEOUS ROCKS OF THE LA SAL MOUNTAINS

The geology of the La Sal Mountains has been described by Hunt (1958) who found that three stocks with associated laccoliths, dikes, sills, and bysmaliths comprise the intrusive igneous cores of the three mountain groups (fig. 34). In the northernmost group of mountains, known collectively as North Mountain, the intrusions include diorite porphyry, monzonite porphyry, syenite porphyry, soda rhyolite, and aegerine granite. The soda rhyolite and aegerine granite are related to a volcanic phase of igneous activity. In the middle group, known collectively as Middle Mountain, laccoliths of diorite porphyry are exposed. A small syenite sill is also present at Middle Mountain, but it is probably part of the North Mountain feldspathoidal series according to Hunt and Waters (*in* Hunt, 1958, p. 344). At South Mountain the laccoliths are predominantly diorite porphyry, plus minor amounts of monzonite porphyry.

The igneous rocks cut the Mancos Shale, hence they are not older than Late Cretaceous. Hunt considers the intrusions to be Tertiary (1958, p. 309), whereas Shoemaker (1954, p. 63) has stated that a latest Cretaceous age for the laccolithic mountains of the Colorado Plateau is not precluded by the available evidence.

Measurements of magnetic susceptibility were made for igneous rocks collected from 115 localities, mostly in the North Mountain group (table 2). Measurements of remanent magnetization were made of 29 specimens. Thirty of the specimens listed in table 2 were contributed by C. B. Hunt; the remainder were collected during the course of this investigation. The sampling was not done in a completely systematic manner on an areal basis, therefore the specimens are only approximately representative of the intrusive rocks of the La Sal Mountains. In addition, the proportion of strongly altered specimens is probably relatively high.

The magnetic susceptibility of most rocks, and hence the magnitude of the induced magnetic field, depends almost entirely on their magnetite content. In the igneous rocks of the La Sal Mountains the magnetite content ranges between virtually zero and several percent, but it does not vary systematically according to rock types. The magnetite content of the rocks depends not only on that present as an original constituent, but also on the amount of alteration. In general, magnetite was destroyed by hydrothermal alteration and by weathering. For the most part, specimens that were apparently unweathered or slightly weathered were collected.

The degree of alteration of the rocks listed in table 2 was estimated by use of a hand lens. This estimate was based mainly on the opacity of the feldspar phenocrysts, and, where observable, by the alteration of the amphibole phenocrysts. Because of the many variables, innumerable specimens—many more than were collected for this study—would be required to determine representative values of magnetic susceptibility of the igneous rocks of the La Sal Mountains.

Table 2 shows susceptibilities listed according to locality, rock type, and relative amount of alteration. The mean susceptibility of the unaltered monzonite porphyry specimens from North Mountain is shown to be

TABLE 2.—*Magnetic susceptibilities of igneous rocks of La Sal Mountains*

[Measurements made by W. E. Huff, U.S. Geol. Survey]

Locality	Rock type	Degree of alteration	Magnetic susceptibility range	Mean (cgs units)	Localities sampled
North Mountain	Diorite porphyry	Slight	0.0008–0.0038	0.0021	37
	do	Moderate to thorough	.0002– .0032	.0011	32
	Monzonite porphyry	Slight	.0017– .0040	.0028	5
	do	Moderate to thorough	.0000– .0016	.0006	11
Middle Mountain	Diorite porphyry	Slight	.0007– .0032	.0019	21
	Diorite(?) porphyry	Moderate to thorough		.0012	2
	Noselite syenite	Slight		.0003	1
South Mountain	Diorite porphyry	do	.0003– .0041	.0026	6

slightly higher than those found for the diorite porphyry; but the difference is probably not significant in view of the small number of monzonite porphyry localities sampled. Rocks that are only slightly altered have higher susceptibilities in general than the more strongly altered rocks, though the range in susceptibilities is so wide that there is considerable overlap (table 2 and fig. 35).

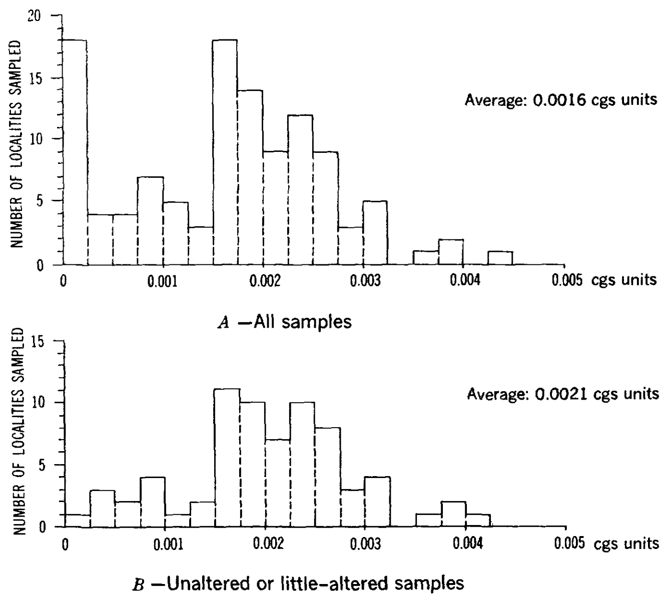

FIGURE 35.—Histograms of magnetic susceptibilities of some intrusive igneous rock of the La Sal Mountains.

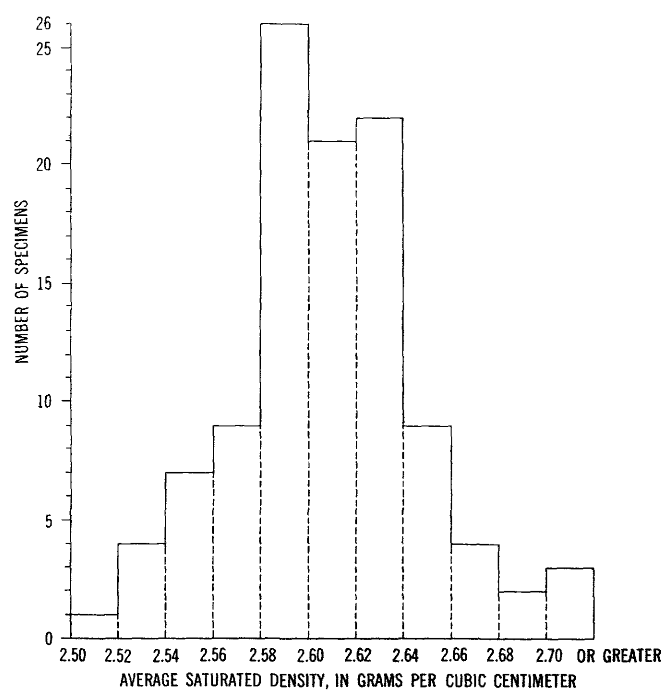

FIGURE 36.—Histogram of densities of intrusive igneous rocks in the La Sal Mountains.

The average susceptibility of all specimens of intrusive rocks was about 0.0016 cgs unit, and that of the unaltered or little-altered specimens was about 0.0021. Because a disproportionate number of altered rocks was collected, the value 0.002 is considered to be roughly representative of the average magnetic susceptibility of the intrusive rocks of the La Sal Mountains.

Remanent magnetization of 29 oriented specimens of intrusive rocks ranged from low to moderate. The direction of remanent magnetization was mainly random in the specimens tested, therefore the magnetic anomalies associated with the La Sal Mountains are probably governed largely by the magnetic susceptibilities of the intrusive rocks.

Densities of 108 specimens of igneous rocks range from 2.51 to 2.81 g per cm^3 (fig. 36). The mean density is 2.61 g per cm^3, with a standard deviation of $\pm$0.04 g per cm^3. Density control is probably adequate for the purposes of this investigation, judging from the relatively small spread of measured densities.

STRUCTURAL GEOLOGY

Three prominent systems of salt anticlines trend northwestward across the area (pl. 14). The anticlines are underlain by ridges of thickened salt of the Paradox Member of the Hermosa Formation. Large valleys have been eroded at intervals along the breached crests of the anticlines. Collapse of the crests by faulting or subsidence is common.

Fisher and Sinbad Valleys lie on the northeast system of anticlines. Salt Valley anticline (Dane, 1935) is a northwestern extension of the system. Normal faults connect the major valleys, probably defining a deep-seated ridge of salt which connects larger salt masses at the valleys (Shoemaker, 1954, p. 53). Castle and Paradox Valleys are the sites of salt anticlines along the middle system. Spanish and Pack Creek Valleys, and Pine Ridge are on anticlines of the southwest system, which includes Moab salt anticline to the northwest. A fourth major system, the Dolores-Lisbon Valley salt anticline, lies south of the La Sal Mountains area (fig. 33).

Although each system of anticlines trends northwestward, the axis of Fisher Valley anticline is offset from that of Sinbad Valley anticline, and the axis of Spanish Valley anticline is offset from the Pine Ridge anticline (pl. 14). These offsets are apparently left lateral, and they may define a deep northeastward-trending transverse structure in the presalt basement, as discussed on pages 106–107.

Summaries of the geologic history of the salt anticlines and related structures have been given by Baker (1933), Dane (1935), Stokes (1948, 1956), Shoemaker

(1954), Cater (1955), Shoemaker and others (1958), and Jones (1959). These reports contain extensive references to the literature on the salt anticlines.

The La Sal Mountains are on a broad structural dome with a relief of at least 3,000 feet. Relief on the dome is locally increased by relief of the salt anticlines and by local doming around the stocks and laccoliths. At North and South Mountains the domes surrounding the intrusions are superimposed on older anticlinal structures. Although the stocks and laccoliths at these mountains were emplaced in older salt anticlines, those at Middle Mountain were emplaced between the two anticlinal systems. The degree of local doming at the three mountain groups is proportional to the diameter of the stocks, and, if the domes were flattened, the space occupied by the stocks would be closed (Hunt, 1958, p. 316).

Sagers Wash syncline, in the northeastern part of the area (pl. 14), marks the approximate boundary between the Paradox basin and Uncompahgre uplift (fig. 33).

Structure contours shown on plate 14 are drawn at the base of the Dakota Sandstone of Cretaceous age. In general, the thickness of beds between the base of the Dakota Sandstone and the base of the Wingate Sandstone of Triassic age is relatively constant, varying no more than 500 feet in the area. There are no major angular unconformities between the Wingate and Dakota Sandstones except locally near the salt anticlines; thus the structure contours also show the approximate configuration of Triassic beds.

AEROMAGNETIC SURVEYS

Aeromagnetic surveys of the La Sal Mountains area (pls. 15, 16) were made in 1955 and 1956, by using a continuously recording AN/ASQ-3A flux-gate magnetometer, installed in a two-engine airplane flying at about 150 miles per hour. East-west lines were flown about 1 mile apart, about 12,500 feet above sea level. Lines were spaced to avoid the highest peaks. Magnetic data were obtained and compiled by standard procedures described by Balsley (1952).

Aerial photographs were used for pilot guidance, and the flight path of the plane was recorded by a gyro-stabilized continuous-strip camera. The magnetic data were plotted on photomosaics, as topographic maps were not available when the area was flown. Errors therefore exist in the positions of some of the flight lines and magnetic anomalies, but they apparently do not effect the results seriously. Other errors of unknown magnitude result from deviation of the plane from its barometrically controlled flight level. The errors are largest close to the higher peaks, where the vertical magnetic gradient is large.

GRAVITY SURVEYS

Worden gravity meters with scale constants of about 0.5 milligal were used throughout the survey. The normal drift rate of the meters was about 0.05 milligal per hour, although the rate was as high as 0.10 milligal per hour in a few traverses. Gravity bases were established at convenient points along the main access roads and were tied at several points to a master base net which originates at the U.S. Coast and Geodetic Survey pendulum gravity station Egnar at Egnar, Colo. (fig. 33). The maximum closure difference at junction points within the base net was 0.3 milligal. Gravity bases were occupied about every 2 hours, when possible, and frequent repeats of gravity readings were made at intervening gravity stations for close drift control.

About 640 gravity stations, including 37 bases, were established. Eighty additional gravity stations from the northern part of the Lisbon Valley area are included on the gravity anomaly map (pl. 17).

About 800 square miles were covered during the survey. Gravity stations were usually spaced 1 to 2 miles apart, although closer spacing was made over the salt anticlines and other areas of special geologic interest. Spacing is wider in difficultly accessible areas.

HORIZONTAL CONTROL

Horizontal control was provided by preliminary editions of multiplex topographic maps (scale 1:24,000) of the La Sal, La Sal Junction, Castle Valley, and Polar Mesa 15-minute quadrangles. Locations of gravity stations were chosen at points that were readily recognizable on the topographic maps.

ELEVATION CONTROL

Elevation control was obtained from U.S. Coast and Geodetic Survey and U.S. Geological Survey bench marks (3 percent), from photogrammetric spot elevations (27 percent), from contour interpolation of the topographic maps ($<$ 1 percent), and from altimetric surveys (70 percent). The range of the surveying altimeters was 7,000 feet and the dials could be read to the nearest 2 feet. Three altimetric methods were used: the single-base method, leapfrog method, and loops between bench marks or spot elevations with one or two altimeters. Descriptions of altimetric methods may be found in standard references, for example, in Breed and Hosmer (1953).

Elevations at bench marks are correct within 1 foot, spot elevations are generally correct within 15 or 20 feet, contour interpolations are assumed to be correct within 40 feet, the map contour interval, and many altimetric elevations are estimated to be correct within 20 feet. About 1 percent of the altimetric elevations were obtained during the course of extended traverses through large ranges of altitude and these elevations may be as much as 40 feet in error.

REDUCTION OF GRAVITY DATA

Gravity data were reduced by standard methods (for example, see Nettleton, 1940, p. 51–61). Theoretical gravity at seal level as a function of latitude was determined from the "International Formula" of spheroidal gravity of 1930. An elevation factor of 0.062 milligal per foot was used in computation of the gravity anomalies. This factor corresponds to a density of 2.5 g per cm^3 as determined in the Uravan area (Joesting and Byerly, 1958, p. 7). The contour values on the gravity anomaly map (pl. 17) are Bouguer anomalies, for the given reference spheroid and reduction density, plus 300 milligals. It should be noted that use of a different reduction density of reasonable value, 2.4 or 2.6 g per cm^3, would not appreciably change the pattern of gravity anomalies shown on plate 17. If 2.6 g per cm^3 were used, negative anomalies would become somewhat more negative and positive anomalies would become somewhat less positive. The reverse would be the case if a density of 2.4 g per cm^3 were used in the reductions.

Corrections for terrain were generally made to distances ranging from 20.3 miles for the stations below 8,500 feet to 104 miles for stations above 11,000 feet. Terrain corrections through zone "J" of Hammer's tables (1939) were applied at most of the stations in the adjoining Lisbon Valley area (Byerly and Joesting, 1959, p. 43). In general, terrain corrections for outer zones were not continued beyond the zone in which the contribution of the terrain was below about 0.7 milligals. Terrain corrections for outer zones were estimated at some stations; the estimates were based on corrections at nearby stations of similar elevation and topographic position.

Gravity anomalies at stations occupying the higher peaks and the floors of the deepest canyons may be 1 to 3 milligals low with respect to the other stations, because of regional terrain effects. The largest terrain correction, 52 milligals, was required for the station on the crest of Mount Tukuhnikivatz. Terrain corrections were 5 milligals or larger at about 20 percent of the gravity stations.

ERRORS IN THE GRAVITY ANOMALIES

Inaccurate determination of elevations is the principal source of error in the reduced gravity values. Most of the elevations are estimated to be correct within 20 feet, equivalent to errors of 1.2 milligals in the gravity values. One percent of the elevations may be as much as 40 feet in error, equivalent to errors of 2.5 milligals in the gravity values.

The errors in calculated terrain corrections probably do not exceed 5 to 10 percent of their values, which range from 0.5 to 52 milligals.

The maximum closure difference at junction points of the base lines was 0.3 milligal. The total drift of the gravity meters during a normal day's traverse did not exceed 1.0 milligal. Because frequent repeats of readings were made at gravity bases and intervening stations it is believed that the maximum error in applying drift corrections did not exceed 0.3 milligal for any traverse. Therefore, the error in "absolute" observed gravity at a given station may be as large as 0.6 milligal, the sum of the maximum error in observed gravity at the bases and the maximum error involved in correction for meter drift. However, the maximum error in observed gravity between adjacent stations is probably only about 0.1 to 0.2 milligal.

Other sources of error include regional terrain effects, neglect of the effect of the curvature of the earth, inaccuracies of calibration of the gravity meters, and nonlinear behavior of their moving systems.

It is estimated that the average relative error in the gravity anomalies is less than 2 milligals across the area surveyed. One or two percent of the anomalies may be in error by as much as 3 or 4 milligals; these are associated with stations on high peaks or in deep narrow canyons.

INTERPRETATION OF THE GEOPHYSICAL DATA

MAGNETIC MAP

Anomalies associated with two distinct sources are shown on the magnetic maps (pls. 15, 16). The broad low-gradient regional anomalies reflect principally structures in the Precambrian basement rocks and variations in the composition of and depth to the Precambrian surface. The high-gradient generally closed local anomalies are associated with the La Sal Mountains laccolithic complex. The regional magnetic effects are shown more prominently on plate 16, from which a latitude gradient was removed. This gradient, which is positive to the north, is about 8.9 gammas per mile along the magnetic meridian in the La Sal Mountains region (U.S. Coast and Geodetic Survey Chart 3077f).

GRAVITY ANOMALY MAP

The most prominent gravity anomalies in the area are gravity lows associated with the salt anticlines that have cores of salt, gypsum, and clastic sedimentary rocks of low average density (pl. 17). Gravity highs are associated with the intrusive igneous rocks of the La Sal Mountains, which are slightly denser than the surrounding sedimentary rocks. Broad positive and negative regional anomalies are related to structural and lithologic changes in the basement rocks and to variations in thickness of the overlying sedimentary rocks. The three groups of anomalies overlap so that isolation of a particular anomaly requires subjective evaluation of their relative importance. Second derivative or residual gravity methods have not been used to isolate anomalies, because they tend to magnify errors which are relatively large in this gravity survey.

In the following interpretation of the magnetic and gravity maps, emphasis has been placed on parallelism or divergence in strike of the contours with the strike of structure contours on Mesozoic reference horizons. Parallelism indicates, in part, that the contours reflect Mesozoic or Cenozoic structures, whereas divergence is considered evidence of pre-Triassic structure. In some places, however, the magnetic and gravity effects of the basement rocks and the gravity effects of salt of the Paradox Member are so strong that this interpretative procedure cannot be followed.

REGIONAL MAGNETIC AND GRAVITY ANOMALIES

MAGNETIC ANOMALIES

In general, the Precambrian basement sources of the regional magnetic anomalies are comparatively deep in the La Sal Mountains area (pls. 15, 16), although no reliable estimates of depth are possible from the magnetic data because of the small amplitude of the anomalies associated with the basement rocks. As noted previously, basement rocks are buried at depths ranging from about 7,800 feet at the Pure 1 Gateway to 17,000 feet at the Continental 1 Scorup in Paradox Valley, just east of the area. The small regional magnetic anomalies indicate that the basement rocks are generally of low to moderate magnetization; and moderate contrasts are indicated by steepened gradients south of South Mountain and along a zone that extends from Paradox Valley to the northern mountain group (North Mountain). Regional gravity anomalies, however, indicate rather large contrasts in the density of the basement rocks. It is therefore likely that these rocks are made up of several types of metamorphosed sedimentary rocks, and possibly also of granitic rocks, which would account for the relatively moderate and uniform magnetization and large density contrasts.

The regional magnetic trends and changes in magnetic gradients are associated mainly with structural trends and compositional changes in the basement rocks. The main magnetic trends are northwesterly over much of the area, in agreement with the regional structural trend of the sedimentary rocks and the strike of the salt anticlines. Just west and northwest of the La Sal Mountains, however, a series of transverse magnetic trends extends southwest across the area, with resulting offset to the left of the northwesterly trends. These transverse trends coincide generally with a prominent gravity trend (the Wilson Mesa regional gradient). They apparently mark a major structural and lithologic discontinuity in the Precambrian basement, which crosses the main regional northwestward-trending structures just west and northwest of the La Sal Mountains.

Several changes in regional magnetic gradient seem to be structurally meaningful. In the southern part of the area a northwestward-trending zone of relatively high gradient passes south of South Mountain, is offset to the southwest by the transverse zone already discussed, and continues west-northwest parallel to Kane Springs Canyon. Farther north a similar zone of higher magnetic gradient extends northwestward from the vicinity of Paradox Valley. This zone is interrupted by the local magnetic effects of North Mounutain but it is present just to the west, where it is also offset to the southwest before resuming its northwesterly trend diagonally across Spanish Valley. These two zones are northwestern extensions of a single high-gradient zone between Gypsum and Paradox Valleys in the Uravan area to the east (Joesting and Byerly, 1958, pl. 2), which split in the La Sal Mountain area. They are related to contrasts in the composition of the underlying Precambrian rocks and possibly to their displacement by faulting or warping.

A broad regional magnetic low lies between the two zones of higher gradient and encompasses all of the La Sal Mountains. This regional low is shown prominently on plate 16, the magnetic map from which a latitude gradient has been removed. West of the mountains the broad low becomes constricted and is offset to the southwest conformably with the higher magnetic gradients. The regional magnetic low coincides closely in outline with a regional gravity high (pl. 17), which will be discussed more fully later. The coincidence indicates lithologic contrasts in the underlying basement rocks and probably of basement relief, along boundaries defined approximately by the regional magnetic and gravity anomalies.

There is no magnetic evidence of a parent body from which the laccolithic complex of the La Sal Mountains was derived; in fact the regional magnetic low shows that the underlying rocks are of moderately low and uniform magnetization. The absence of other than inverse magnetic effects that might be attributable to a parent igneous body does not preclude the possibility of its existence. It indicates, however, that any such body lies at a depth below which magnetic effects disappear. Vacquier and Affleck (1941) estimate this depth to be between 11 and 14 kilometers beneath the surface, which is also about the estimated depth at which the Curie point for magnetite-bearing material is reached. If appreciable titanium oxide is associated with the magnetite, the Curie point would be reached at a lower temperature and smaller depth.

The magnetic evidence suggests that the igneous rocks at North and South Mountains were intruded near the intersections of major northwestward and southwestward-trending zones of basement displacement. Significantly, the salt anticlines of Paradox and Castle Valleys are along the same northwestward-trending zone as North Mountain; and the Gypsum Valley, Pine Ridge, and Spanish Vally salt anticlines occur along the same zone as South Mountain. The apparent left-lateral offset of the salt anticlines near the La Sal Mountains is interpreted to be related to a transverse structure that continues northeasterly toward the Uncompahgre structural front northeast of the Dolores River.

The positive northerly magnetic gradient along the Dolores River in the northeastern part of the area is a continuation of a strong trend along the Uncompahgre uplift (Joesting and Byerly, 1958, pl. 2). It reflects the effect of more strongly magnetic Precambrian rocks in the Uncompahgre Plateau, and possibly of increasing magnetite content of the crystalline rocks toward the uplift. The positive gradient is not believed to be associated with shallower basement, as the gravity and structural evidence indicate that the basement is comparatively deep along Sagers Wash syncline (fig. 34 and pl. 17).

GRAVITY ANOMALIES

The most prominent regional gravity anomalies are steepened gravity gradients south of Spanish Valley, west of the La Sal Mountains, and between the northern group of peaks (North Mountain) and Paradox Valley (pl. 17). South of Spanish Valley gravity contours trend westward and northwestward, decreasing from 116 milligals near Kane Springs Canyon to about 70 milligals in Spanish Valley; gravity values then gradually increase to about 84 milligals near Negro Bill Canyon. This westward-trending steepened gradient is termed the "Spanish Valley regional gradient." Salt thickening of 7,000 to 10,000 feet at Spanish Valley can account for as much as 30 milligals of the gradient from Kane Springs Canyon to Spanish Valley, but there remains a residual decrease of 16 milligals which must be explained by density changes or structural relief, or both, in the basement rocks. Basement rocks are probably less dense or deeper under Spanish Valley than to the south. This regional gravity gradient continues westward, into the Inter River area north of Upheaval Dome (Joesting and Case, 1960, fig. 114.3; Joesting and Plouff, 1958, p. 89, 91), diverging from Spanish Valley salt anticline.

The estimated elevation of the Precambrian surface is 3,000 feet below sea level at the Humble 1 Bridger, just southwest of Spanish Valley (fig. 34). It is 7,000 feet below sea level at the Delhi-Taylor 2 Utah (sec. 18, T. 25 S., R. 21 E., Salt Lake meridian) on Moab anticiline, 14 miles northwest of the Humble well (fig. 34). Part of the Spanish Valley regional gradient is undoubtedly caused by the 4,000 feet of presalt basement relief across the southwest flank of Spanish Valley.

Near Pack Creek at the southwest end of Spanish Valley the steepened regional gradient changes abruptly in trend and continues northeast across South and Wilson Mesas to the northwest flank of North Mountain. The gravity values decrease from 116 milligals at Geyser Pass to 86 milligals at Wilson Mesa—a decrease of 30 milligals in 8 miles. The steep gradient, termed here the "Wilson Mesa gradient," can be partly explained by the positive gravitational effects of the igneous intrusions of the mountains, combined with the negative effect of thickened salt at Spanish and Castle Valleys. However, analysis of these combined effects indicates that at least 20 milligals of the gradient is due to changes in the density or relief of the pre-Paradox rocks, or to a combination of the two. The northeast gravity trend agrees with the magnetic trends previously discussed, which indicates that the gravity trends are caused, in part at least, by Precambrian rocks. Furthermore, the northeast gravity trend is generally transverse to the structure of the Triassic and younger beds (pl. 14) which emphasizes the pre-Triassic age of the source of the gradient.

In the absence of subsurface control between the La Sal Mountains and Spanish Valley, it is not possible to determine the relative importance of basement relief, intrabasement density contrasts, salt thinning, and the laccolithic intrusions in producing the Wilson Mesa regional gradient.

To set reasonable limits on the sources of the regional gradient, the gravitational effects of two models have been computed (fig. 37) using standard methods of graticule analysis described by Hubbert (1943). It has been assumed that the source of the gravity anomaly is two dimensional, that is, its length is great with respect to its width. The models do not yield a total anomaly as large as that observed, hence they are conservative in that larger basement relief, more salt thinning, or larger intrabasement density contrasts would be required to reproduce the total observed anomaly. It

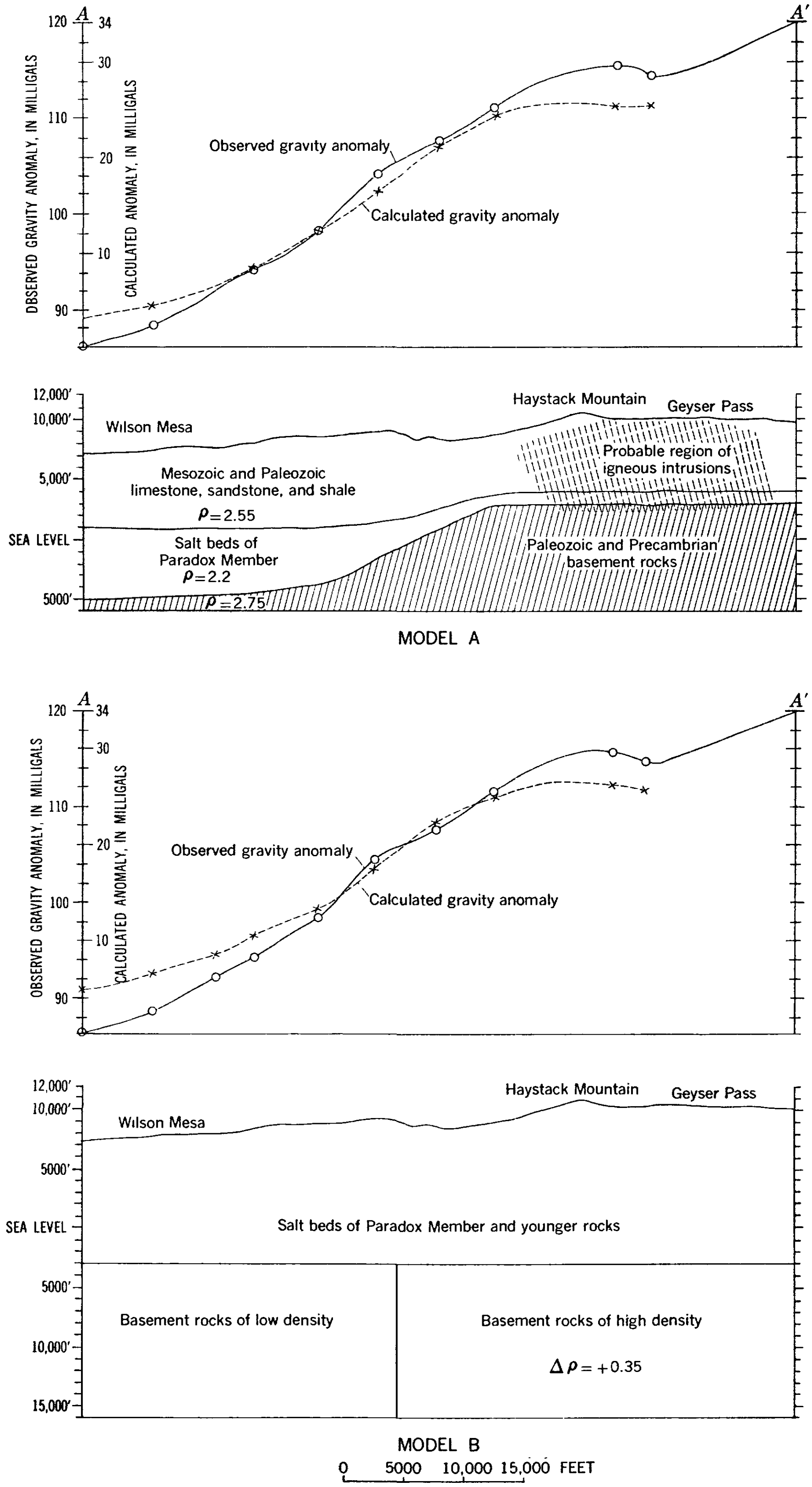

FIGURE 37.—Two interpretations of the Wilson Mesa regional gravity gradient.

must be noted that the models shown on figure 37 are greatly simplified and are therefore only approximately representative of possible geologic conditions at depth.

On model A (fig. 37), the pre-Paradox sedimentary rocks are included with the Precambrian rocks because they are probably of nearly the same density. The density of 2.75 g per cm³ that has been assigned to this presalt basement may be somewhat too high, but a lower density would require a correspondingly greater basement relief. The basement relief from Wilson Mesa to Geyser Pass is assumed to be 8,000 feet. The salt of the Paradox, of density 2.2 g per cm³, is assumed to thin from 6,000 feet at Wilson Mesa to 1,000 feet beneath Geyser Pass. The relief of the top of the salt is assumed to be about 3,000 feet, the same as the known structural relief of Mesozoic rocks between Wilson Mesa and Geyser Pass. Such complementary salt thinning with large basement relief may imply that the basement relief occurred during deposition of salt of the Paradox. The beds overlying the salt have been assigned an average density of 2.55 g per cm³, which is considered to be a reasonable average value for the Mesozoic and uppermost Paleozoic beds, and for the igneous intrusions that are present near Geyser Pass.

East of the southeast end of the profile, at *A′*, the basement probably drops steeply toward Paradox Valley, hence the anomalous density distribution is assumed to end at *A′*.

On the model B (fig. 37) the source of the Wilson Mesa regional gradient is assumed to lie entirely in the presalt basement, with horizontal beds resting on the presalt basement. Within the basement a density contrast of 0.35 g per cm³ is assumed across a vertical fault, the region of higher density being under the mountains. This density contrast is shown extending from 3,000 to 16,000 feet below sea level. A better fit could be obtained by appropriate changes in the inclination of the fault; or in the density contrast, depth to basement, or thickness of the zone of contrasting density, but such refinements are not warranted because of the lack of subsurface control.

Both models are probably extreme in their configuration and in the density contrasts assumed. It is unlikely that basement relief is as great as 8,000 feet between Wilson Mesa and Geyser Pass, and that density contrasts as large as 0.35 g per cm³ are present in the upper part of the presalt basement. We believe the anomaly is caused by some intermediate combination of basement relief, salt thinning, and intrabasement density contrasts. Both models indicate that a structural zone involving the presalt basement exists parallel to the Wilson Mesa regional gradient.

The Wilson Mesa regional gradient apparently ends near the northwest flank of the North Mountain group of peaks. A flatter gravity gradient continues northeasterly across Polar Mesa and North Beaver Mesa to the Dolores River, but a more pronounced gradient swings abruptly around the north flank of North Mountain and continues to the southeast toward Paradox Valley. This regional gradient parallels the northeast side of North Mountain and the southwest limb of the Paradox Valley salt anticline, hence it is termed the Paradox Valley regional gradient. It continues along most of the length of Paradox Valley in the Uravan area (Joesting and Byerly, 1958, p. 12, pl. 3), and corresponds to an inferred basement fault along the southwest flank of Paradox Valley (Joesting and Case, 1960, figs. 114.2 and 114.3).

From the eastern flank of the La Sal Mountains to Buckeye Reservoir, at the head of Paradox Valley, the gravity values decrease from 116 to 90 milligals. The gravitational effects of the igneous intrusions of the La Sal Mountains are probably at a minium here, so that a reasonable estimate of the magnitude of the gradient can be made. Smoothing of regional gravity contours suggests that no more than 10 milligals of the decrease is due to the effects of thickened salt along the northwest extension of the Paradox Valley salt anticline. Near Buckeye Reservoir the effects of the igneous intrusions are relatively small, as the nearest outcrops of diorite porphyry are 7 miles away at Mount Peale. Thus, the decrease of at least 16 milligals across the Paradox Valley regional gradient may be explained in part by deeper basement rocks under Paradox Valley and Beaver Mesa than under the area southwest of Buckeye Reservoir. A steep drop in the presalt basement surface across the Paradox Valley regional gradient is indicated by data from the Continental 1 Scorup in Paradox Valley and the Shell 1 Wray Mesa Unit 5 miles southwest of the Continental 1 Scorup (fig. 34). Original depositional thickening of the Paradox Member of the Hermosa Formation toward the northeast may also explain part of the gradient. If such depositional thickening took place at the base of the Paradox Member, and, if the gradient is largely caused by it, the sharpness of the gradient indicates faulting in Paradox time, perhaps contemporaneous with salt deposition.

GRAVITY AND MAGNETIC HIGHS NORTHWEST OF THE LA SAL MOUNTAINS

A broad gravity high extends from the Hubbard 1 Government across Professor Creek to Negro Bill Canyon northwest of the La Sal Mountains. Gravity lows over the salt anticlines at Fisher and Castle Valleys are superimposed on this regional gravity high. The high coincides generally with a broad magnetic high (pl.

16) whose axis extends southwestward parallel to the Colorado River. Such coincidence of gravity and magnetic highs indicates that the basement is probably more dense and highly magnetized near Professor Creek than near Negro Bill Canyon. Regional depositional thickening of salt toward Negro Bill Canyon may also contribute to the gravity anomaly.

GRAVITY LOW NEAR THE DOLORES RIVER

Along the Dolores River a regional gravity low coincides with the Sagers Wash syncline, which involves beds as young as the Mancos Shale of Late Cretaceous age just north of the area shown on plate 14. The low represents deep and possibly low-density basement rocks, but it probably does not reflect the effect of thick salt because the proportion of clastic material in the Paradox Member is undoubtedly large in this region near the Uncompahgre front.

A saddle in the gravity contours is seen near the Pure Gateway 1, coinciding generally with a broader saddle in the structure contours. Therefore, the gravity contours probably partly reflect post-Mancos structural movements.

GRAVITY AND MAGNETIC HIGHS SOUTHWEST AND SOUTH OF SOUTH MOUNTAIN

The gravity high which extends westward from South Mountain to Kane Springs Canyon is related partly to thinning of low-density salt between the Spanish Valley-Pack Creek salt anticline to the north and the Lisbon Valley salt anticline to the south (Byerly and Joesting, 1959, p. 45–46). The high is at the southern margin of the Pack Creek regional gradient, and may therefore also be related to dense or shallow basement rocks.

The steepened regional magnetic gradient south and southwest of South Mountain (pls. 15, 16) is offset to the left by the transverse magnetic trend already discussed. North of this gradient the basement is more magnetic and possibly shallower, but no reliable estimates of depth could be made because the flight lines are nearly parallel to the magnetic trend. The magnetic high southwest of Spanish Valley coincides in part with the gravity high at Kane Springs Canyon, and may partly reflect a shallow ridge bounding the deeper part of the salt basin to the north. In general, the magnetic trends and gradients in the south part of the area probably reflect Precambrian compositional and structural trends more nearly than the gravity anomalies, as the latter are influenced by contrasts in the density and thickness of the sedimentary rocks as well as in the crystalline basement. East-west trends of gravity and magnetic contours indicate that Precambrian compositional and structural trends are nearly east-west to the south and west of South Mountain.

CONFIGURATION OF THE BASEMENT SURFACE

Little is known of the configuration of the Precambrian surface in the La Sal Mountains area because of the scarcity of deep wells and because most of the magnetic anomalies are not suitable for depth estimates. However, a few wells in or near the margins of the area allow estimation of the depth to the basement when combined with gravity and magnetic data (fig. 34).

The Delhi-Taylor 2 Utah was drilled completely through the core of the Moab salt anticline and reached the lower member of the Hermosa Formation at an elevation of about 5,000 feet below sea level (Hite, 1961, fig. 1). Assuming 2,000 feet of pre-Pennsylvanian beds, the elevation of the top of the Precambrian is about 7,000 feet below sea level. There is probably relatively little basement relief between the Delhi-Taylor well and Wilson Mesa, based on flat regional gravity and magnetic gradients (Joesting and Case, 1960, figs. 114.2 and 114.3), so the elevation of the Precambrian surface at Wilson Mesa can also be assumed to about 7,000 feet below sea level.

In the analysis of the Wilson Mesa regional gradient (fig. 37) two extremes of basement relief were shown in the region between Wilson Mesa and Geyser Pass—8,000 feet of basement relief (model A) and no basement relief (model B). From these extreme estimates, we have chosen an intermediate basement relief of about 4,000 feet between Wilson Mesa and Geyser Pass, thus the elevation of the top of the Precambrian at Geyser Pass may be on the order of 3,000 to 4,000 feet below sea level.

Precambrian rocks were penetrated at an elevation of 4,668 feet below sea level at the Shell 1 Wray Mesa Unit, just east of the La Sal Mountains area. Between Geyser Pass and the Shell well, the basement probably drops about 1,500 feet. The Continental 1 Scorup was drilled through the core of Paradox Valley salt anticline (Jones, 1959, p. 1888) and rocks of Mississippian age were found at a depth of 14,700 feet or about 9,700 feet below sea level. The top of the Precambrian is estimated to be about 11,000 feet below sea level, assuming 1,300 feet of pre-Pennsylvanian beds. Therefore, if our assumptions are correct, the Precambrian surface drops 8,000 feet between Geyser Pass and Paradox Valley and about 6,300 feet between Wray Mesa and Paradox Valley. The dropoff in the basement coincides with the Paradox Valley regional gravity gradient.

In Sinbad Valley salt anticline, the Huber 1 Sinbad (sec. 16, T. 49 N., R. 19 W., New Mexico principal meridian) bottomed in evaporites of the Paradox Member at a depth of 10,300 feet, or at 4,800 feet below sea level (Shoemaker and others, 1958, p. 43, 58). If the well reached almost to the bottom of the Paradox Member, and if there are 1,200 feet of beds of pre-Paradox age, the elevation of the Precambrian surface is about 6,000 feet below sea level. On the other hand, if the total column of salt at Sinbad Valley anticline is as thick as at Paradox Valley, 14,700 feet, and if there are 1,300 feet of beds of pre-Paradox age, the Precambrian surface is 10,500 feet below sea level. Between these limits we have arbitrarily estimated the top of the Precambrian surface at 9,000 feet below sea level at Sinbad Valley, weighting our estimate toward the deeper limit because regional gravity and magnetic contours indicate relatively little basement relief between Paradox and Sinbad Valleys.

Along the structural front of the Uncompahgre uplift, the top of the Precambrian is 3,100 feet below sea level in the Pure 1 Gateway. Therefore, between the Pure 1 Gateway and Paradox Valley, the basement drops about 8,000 feet. Both gravity and magnetic gradients between Paradox Valley and the Pure well indicate that most of this relief takes place in a relatively restricted zone that coincides with the northeast flank of Sagers Wash syncline. The saddle in the form lines of figure 34, southwest of the Pure 1 Gateway, is based on saddles in the structure contours (pl. 14) and in the gravity contours (pl. 17). Just north of the area shown in figure 34 the Richfield Onion Creek (sec. 31, T. 23 S., R. 24 E.) bottomed in the Paradox Member at an elevation of 9,615 feet below sea level. The Precambrian basement is probably about 11,000 feet below sea level.

Deep wells are comparatively abundant southeast and southwest of the La Sal Mountains. As noted previously, the Humble 1 Bridger southwest of Spanish Valley bottomed in Cambrian strata at an elevation of 2,520 feet below sea level. Precambrian rocks are probably about 500 feet deeper, at an elevation of 3,000 feet below sea level. The E. B. La Rue 1 Government (sec. 15, T. 27 S., R. 22 E., Salt Lake meridian) near the southwest flank of Spanish Valley penetrated Mississippian strata at 1,755 feet below sea level and Precambrian rocks are estimated to lie at 3,700 feet below sea level, assuming 2,000 feet of Mississippian, Devonian, and Cambrian beds. The drop in the basement surface between the Humble well and the Delhi-Taylor well on Moab Valley anticline is about 4,000 feet. The California Co. 1 Muleshoe (sec. 2, T. 28 S., R. 23 E.) penetrated Mississippian beds at 3,388 feet below sea level; Precambrian basement is estimated to lie at about 5,000 feet below sea level. Much of this basement relief probably coincides with the Spanish Valley regional gravity gradient. The Pure 1 La Sal (sec. 19, T. 29 S., R. 24 E.) penetrated Mississippian beds at 3,145 feet below sea level; Precambrian basement is estimated at 4,800 feet below sea level.

Other wells near the Colorado River that provide control on the configuration of the Precambrian surface are shown on figure 34. A number of deep wells have been drilled near Lisbon Valley anticline, just south of the area shown on figure 34. They indicate that the basement surface is very irregular and that Lisbon Valley anticline apparently is underlain by a grabenlike depression.

Geophysical and well data thus indicate that the three segments of the large regional gravity gradient outline a zone of more dense or shallower basement rock or thinner salt (or all three) south of and beneath the La Sal Mountains, and a broad region of less dense or deeper basement rocks or thicker salt (or all three) under Beaver Mesa and Spanish, Castle, and Paradox Valleys (fig. 34). The nature of the boundary between these two broad zones is not known, but basement faults are probable, especially near North Mountain and Paradox Valley.

The northeastward-trending basement structure along the west flank of the La Sal Mountains, extending to the Uncompahgre uplift near the Dolores River, is part of a broader regional pattern of transverse basement structures in the central Colorado Plateau which is en echelon with the Colorado mineral belt (Case and Joesting, 1961).

GRAVITY AND MAGNETIC ANOMALIES ASSOCIATED WITH SALT ANTICLINES

SINBAD VALLEY-FISHER VALLEY SALT ANTICLINE

In the following analysis of the gravity anomalies of the salt anticlines, estimates of the densities of their cores are based on the supposition that evaporites near the Uncompahgre front contain a higher proportion of clastic material and are therefore denser than those farther southwest. Thus, a density of 2.25 g per cm^3 has been assumed for the core of Castle Valley anticline and 2.30 for the core of Fisher Valley anticline, as the latter is closer to the structural front.

A gravity low of about 16 milligals is associated with Sinbad Valley salt anticline. The Huber 1 Sinbad, near the center of the valley (fig. 34), bottomed in evaporites after penetrating about 10,300 feet of evaporites and clastic material. In an earlier report, Shoemaker and others (1958, p. 43) estimated from well logs that the composition of the core of the Sinbad Valley anticline includes 42 percent evaporites and 58 percent clastic material. Assuming that the density of the evaporites is 2.2 g per cm^3 and the density of the clastic material is 2.5 g per cm^3, the average density of the material in the core is about 2.37 g per cm^3.

Reanalysis of logs of the Huber well indicates that the proportion of clastic material in the core of the anticline is probably less than originally estimated, being about 33 percent rather than 58 percent (C. L. Jones, D. P. Elston, and E. M. Shoemaker, written communication, 1961). Therefore, the average density of material in the core is probably about 2.3 g per cm^3. If this is correct, the vertical extent of the core of the anticline may be less than 11,000 feet.

A magnetic high just southwest of Sinbad Valley (pl. 14) is probably associated mainly with higher magnetization of the basement rocks, although it may result in part from shallower basement. Ordinarily the effects of basement topography cannot be distinguished from those of small contrasts in magnetization. This anomaly, together with a similar magnetic high in the Uravan area to the southeast (Joesting and Byerly, 1958, pl. 2) is alined with the Sinbad Valley salt anticline and may indicate basement control.

Northwest of Sinbad Valley a gravity low follows a graben system toward Fisher Valley; changes in trend of the gravity low correspond to changes in trend of the graben system. Thus Sinbad Valley salt anticline is offset to the northeast with respect to the Fisher Valley salt anticline, as shown by the surface structure and the gravity contours.

The residual gravity low associated with the Fisher Valley salt anticline is about 18 milligals. Figure 38 shows an interpretation of the anomaly over the valley. The surficial margins of the salt core were picked from a map of Shoemaker (1954), and the subsurface configuration and distribution of rock densities were adjusted to yield a computed anomaly agreeing with the observed anomaly. The computed vertical extent of the core is about 10,000 feet, when densities of 2.3 and 2.55 g per cm^3 are assumed respectively for the core and for the beds outside the core.

A gravity low continues westerly from the northwest end of Fisher Valley. The low, which is nearly parallel to but slightly north of a fault system (pl. 14) in the central part of T. 24 S., R. 23 E. (Salt Lake meridian), is probably related to a zone of thickened salt connecting the core of the Fisher Valley anticline with the core of the Cache Creek–Salt Valley anticline.

There is little gravity or magnetic evidence that basement structures coincide with the Fisher Valley anticline. The magnetic map indicates that compositional trends of the basement rock cross the axis of Fisher Valley.

PARADOX VALLEY-CASTLE VALLEY SALT ANTICLINE

Gravity and well data indicate that the amplitude of the salt core of the Paradox Valley anticline is about 10,000 feet (Joesting and Byerly, 1958, p. 14–15; Jones, 1959, p. 1888). The gravity low over Paradox Valley continues northwest past Buckeye Reservoir, toward North Mountain, and is terminated by the northwestward-trending Paradox Valley regional gradient and the gravity high associated with the laccolithic intrusions at North Mountain. The abrupt decrease in the amplitude of the negative anomaly near Buckeye Reservoir indicates that the vertical extent of the anticline decreases toward North Mountain. There is no gravity evidence of thickened salt northeast of the SE¼ T. 23 S., R. 25 E. (Salt Lake meridian) at the county line (pl. 17).

Castle Valley is underlain by a salt anticline, the southeastern part of which has been intruded by the laccoliths at North Mountain. The shape of the gravity contours indicates that thickened salt extends beneath at least the northwestern part of North Mountain. The residual gravity low associated with the salt core of Castle Valley is about 16 milligals. An interpretation of the anomaly is shown in figure 39. In the analysis a density of 2.25 g per cm^3 was assumed for the salt core and the average density of the adjacent rocks was assumed to be 2.55 g per cm^3. The gravity effects of Round Montain, an intrusive body of diorite porphyry, complicate the gravity minimum in the center of Castle Valley. Therefore the residual gravity low may be somewhat more positive than if the igneous body were not present, and the computed vertical extent of the salt core may be too small. The computed amplitude is about 7,000 feet.

Evidently the intrusive body that forms Round Mountain is too small to produce measurable magnetic effects at the altitude at which the survey was flown. The flight altitude was 12,500 feet and the altitude of Round Mountain is 6,184 feet. Samples of the unweathered diorite porphyry contained magnetic minerals in about the same proportion as those from the La Sal Mountains.

PINE RIDGE-PACK CREEK VALLEY-SPANISH VALLEY SALT ANTICLINES

The geologic map (pl. 14) shows that the Pine Ridge salt anticline is alined with the laccolithic intrusions of South Mountain. The gravity trough southeast of South Mountain indicates that thickened salt underlies the intrusions, although gravity coverage is sparse. The gravity anomaly over Pine Ridge anticline has been analyzed by Byerly and Joesting (1959, p. 48–49).

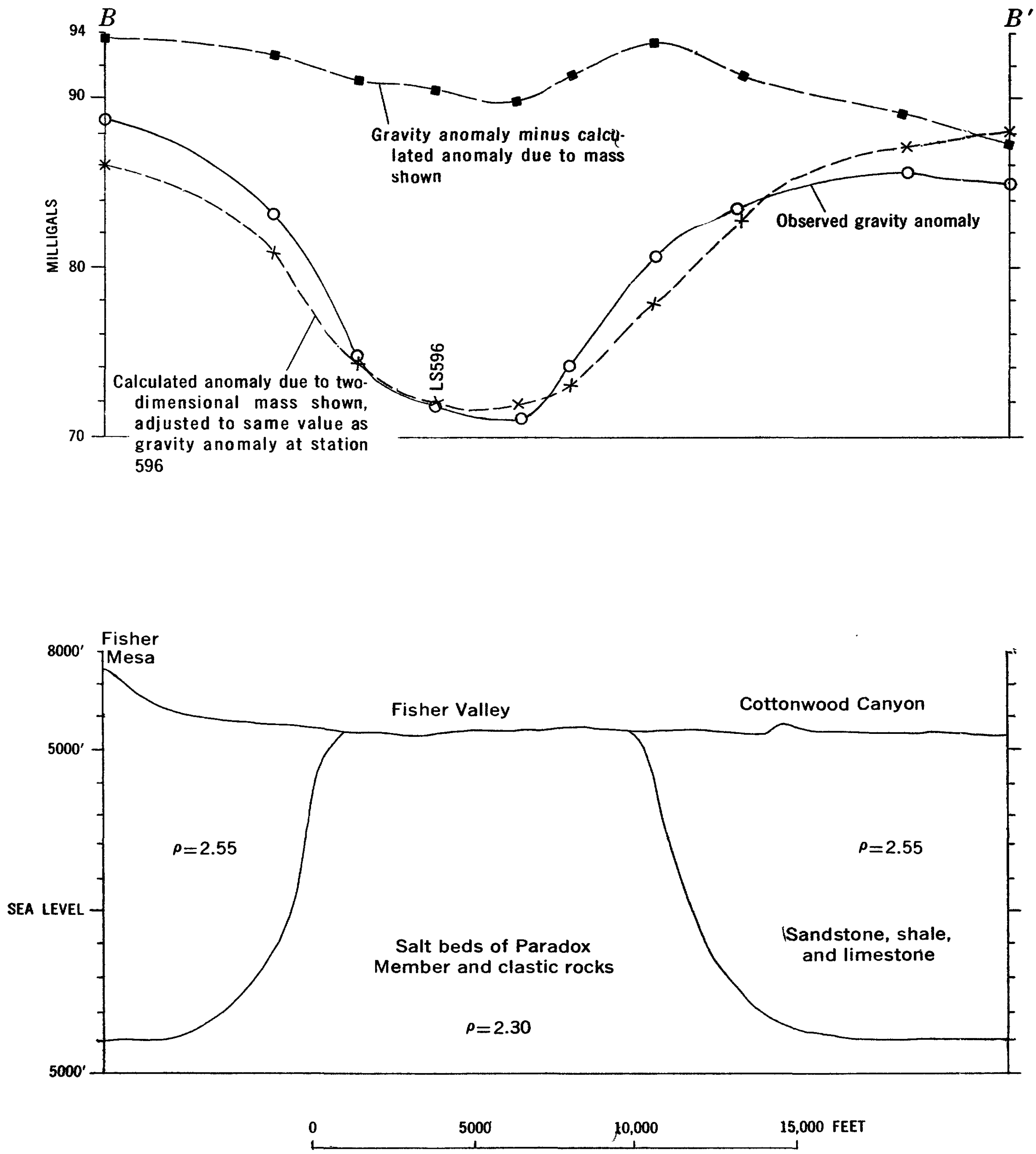

FIGURE 38.—A two-dimensional analysis of the gravity anomaly at Fisher Valley.

The negative anomaly along Pack Creek is an extension of the anomaly over Spanish Valley, although the gravity contours have a different trend. Thickened salt undoubtedly underlies the Pack Creek synclinal graben. There is no geophysical evidence that a discrete salt anticline is present, but rather that the Spanish Valley salt anticline continues at least as far as South Mountain, and thickened salt probably extends at least partly under South Mountain. The Wilson Mesa and Spanish Valley regional gradients obscure the anomaly at Pack Creek, so that quantitative analysis of the Pack Creek anomaly is not feasible.

MAGNETIC AND GRAVITY ANOMALIES ASSOCIATED WITH LACCOLITHIC INTRUSIONS

MAGNETIC ANOMALIES

Agreement is generally good between the magnetic anomalies associated with the La Sal Mountains and the extent of the intrusive rocks, as determined by exposures and inferred from the structure of the enclosing

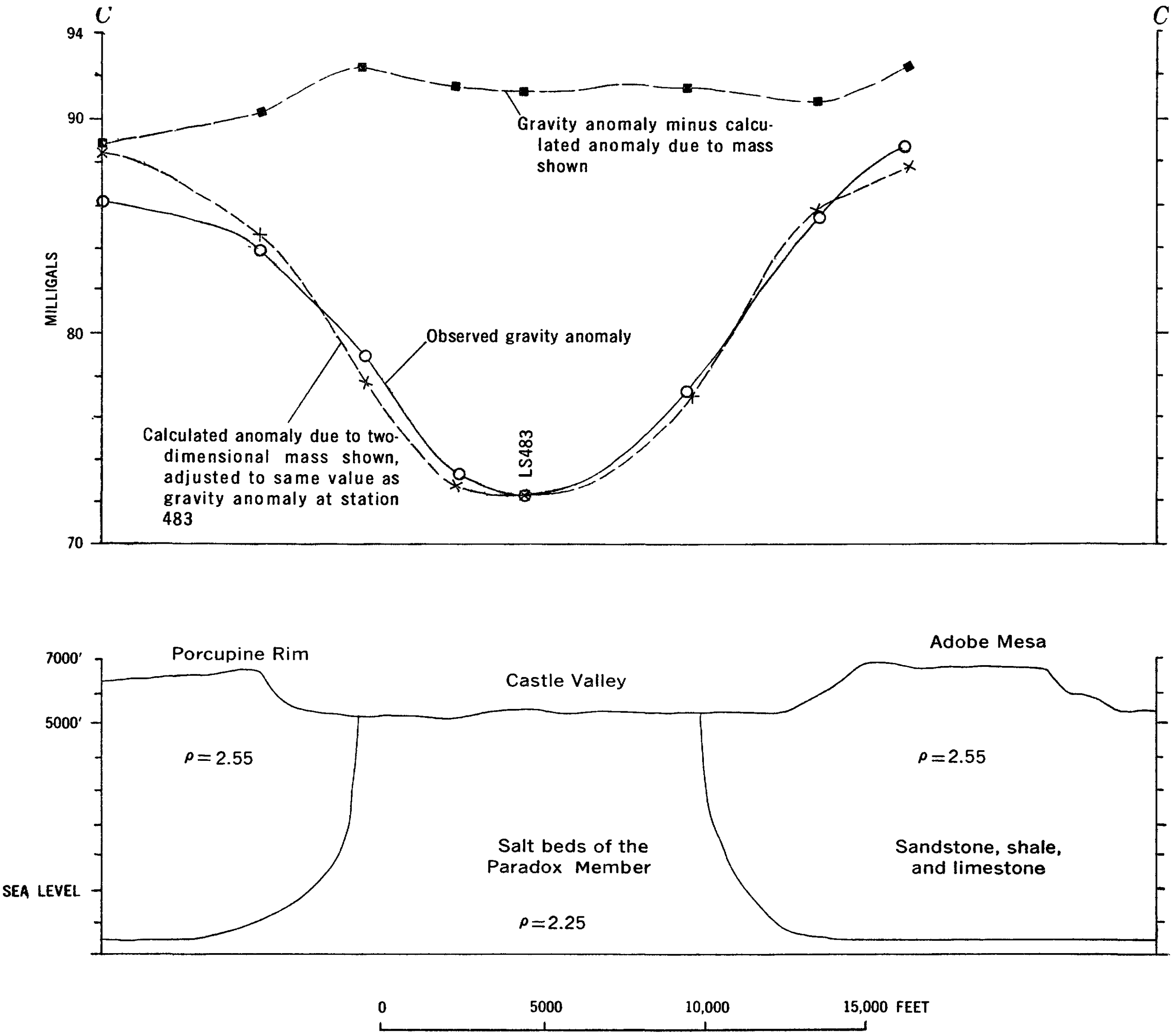

FIGURE 39.—A two-dimensional analysis of the gravity anomaly at Castle Valley.

sedimentary rocks (pl. 14, 15, 16). The amplitude and shape of the anomalies over the higher mountains are governed to a considerable extent by the shape of the upper surface of the intrusions, as well as by their thickness and by contrasts in their magnetization. Except along flight lines, the magnetic contours over the higher mountains are generalized, as the lines were spaced too far apart to permit detailed magnetic mapping.

Magnetic highs were recorded where flight lines passed over or near most of the higher peaks, because they were comparatively close to the magnetic intrusive rocks in the peaks. Thus magnetic highs were found associated with Mount Tomasaki and Haystack Mountain in the northern group; Mounts Mellenthin, Tukuhnikivatz, and Peale in the middle group; and South Mountain. The amplitudes of the highs were governed to a large extent by the closeness of the flight lines to the peaks.

No discrete high was recorded near Manns Peak in the northern group, but rather a broad high over the lower ground about a mile west, apparently because the rocks near Manns Peak are hydrothermally altered and hence are less magnetic than the rocks farther west (Hunt and Waters, *in* Hunt, 1958, p. 335 and pl. 39.). Near Mount Waas the magnetic high is also farther west than might be anticipated, again probably because the rocks in the north La Sal stock, just west of Mount Waas, have been hydrothermally altered (Hunt and Waters, *in* Hunt, 1958, p. 325–339 and pl. 40); and they are less magnetic than the laccoliths west of the stock. Flight lines both north and south of Mount Waas pass over lower ground and are too far away to record the maximum effect of the Mount Waas laccolith.

The laccoliths extending northwest, north, and northeast from the main intrusions of the North Mountains group are evidently comparatively thin, and for the most part lie several thousand feet below the altitude of the magnetic survey. Their magnetic effect is therefore small.

In the Middle Mountain group the Mount Mellenthin laccolith and associated intrusions just to the southwest are evidently comparatively thin and less magnetic than the main intrusions at Mounts Tukuhnikivatz and Peale. Their associated anomalies are small despite their high altitudes.

On the basis of the magnetic survey the intrusions of Middle and South Mountain are apparently more uniformly magnetized than those of the North Mountain complex, possibly because of less differentiation and less alteration. A residual low just south of South Mountain, however, may be caused in part by comparatively low magnetization, though it is probably related mainly to topography.

The broad magnetic lows north and northeast of North, Middle and South Mountains are polarization lows for the most part, resulting from the magnetization of the intrusions in the inclined field of the earth. The forms of the lows are modified by irregularities in the shape, thickness, and magnetization of the intrusions, and by regional effects that originate in the underlying basement. At North Mountain the laccoliths that extend north and northeast from Mount Waas have a slight positive effect, so that the magnetic minimum is farther southeast than if the intrusive complex were simpler in form. At Middle Mountain the polarization low is also modified by the small intrusions north of Mounts Peale and Tukuhnikivatz.

The magnetic low north and northeast of South Mountain is probably accentuated and extended by regional effects, because the local anomaly associated with South Mountain is near the southwestern boundary of the regional magnetic low already discussed. Similarly, the magnetic lows that surround the local highs at Middle Mountain are probably in large measure accentuated and broadened by the regional low. The polarization lows associated with both North Mountain and South Mountain are also accentuated slightly because of the finite thickness of the laccolithic intrusions.

The magnetic map shows little evidence of remanent magnetization of the intrusions along directions different from the earth's present magnetic field. Low altitude, and low magnetic susceptibility possibly due to alteration of the Middle Mountain stock, rather than inverse magnetization, are probably partly responsible for the low 1.5 miles northwest of Mount Tukuhnikivatz. Inverse magnetization may also be partly responsible for the position of the restricted minimum at La Sal Pass, but it could also be produced by normal magnetization of intrusions of irregular shape and contrasting susceptibility.

Figure 40 shows an assumed section across the North Mountain intrusive mass at *D–D′* (pls. 14, 15, 16). The accompanying computed magnetic profile associated with the mass approximately matches the measured profile, assuming that the mass has a uniform magnetic susceptibility contrast of 0.002 cgs unit. The magnetic profile was computed with the aid of a two-dimensional solid-angle polar chart (Pirson, 1935).

The upper surface of the exposed intrusive mass was taken from topographic maps, but it was smoothed to permit closer comparison of computed magnetic effects with those measured from a plane 1,000 feet and more above the surface. The northeast end of the intrusion is in agreement with the mapped contacts at the surface; but a vertical southwest contact was drawn rather than one dipping about 45° SW., as called for by surface structure, to get better agreement between the computed and measured magnetic anomalies. The bottom of the body was assumed to be horizontal; its position was shifted until the computed magnetic profile agreed fairly closely with the profile taken from the aeromagnetic map.

The computed and measured anomalies are in reasonably close agreement when the base of the intrusion is 9,000 feet above sea level; that is, when its maximum thickness is about 2,500 feet. A slightly better agreement could have been achieved by decreasing the dip at the northeast end and extending the body farther downdip, and by decreasing the thickness of the mass, especially at the southwest end. Such refinements are not warranted, however, in view of the simplifying assumptions that were made.

The important implication of figure 40 is that the thickness of the laccolithic intrusion at section *D–D′* is not more than 2,500 feet, exclusive of feeder stocks, if the chosen contrast in susceptibility is not seriously in error. It therefore seems likely that evaporites remain under the laccolithic intrusion, and that thickened salt extends from Paradox Valley as far northwest as Mount Tomasaki. The gravity data in the extremely rugged area near Mount Tomasaki are not sufficiently accurate or detailed to permit removing comparatively large regional effects in order to examine local effects that might be related to minor salt thickening.

Across the main mass of North Mountain at Mount

Waas, satisfactory agreement between measured and computed magnetic profiles was not possible without making unwarranted assumptions about the shape and dimensions of the intrusive complex. The best general agreement was obtained by computing the magnetic effects of a mass about 4,500 feet thick, with a horizontal base about 7,000 feet above sea level, and by ignoring the effect of the stock at greater depths. These computations therefore merely imply what has already been inferred from geologic mapping: that the intrusion is thicker at the central stock near Mount Waas than farther southeast. They do not prove the absence of a stock.

Figure 41 shows an assumed section across the South Mountain intrusive mass at *E–E′* (pls. 14, 15, 16), together with measured and computed magnetic profiles. The same assumptions of susceptibility contrast and the same method of computation was used as for the profile on figure 40. The topographic profile of the upper surface of the intrusive body was smoothed to permit more valid comparison with the aeromagnetic data. The northeast and southeast sides are in agreement with the position and attitude of the intrusive contacts, as indicated by contacts at the surface and the structure of the overlying sedimentary rocks, but the sides arbitrarily cut off vertically at depth. A two-dimensional mass was assumed, which resulted in a computed anomaly about 10 percent larger than that from a three-dimensional mass. This error is not significant in view of errors that probably result from the other simplifying assumptions.

The northeastern part of the computed profile deviates considerably from the measured profile. A better match could have been obtained by flattening the northeast contact to about 20° instead of 45°, and by extending the mass farther downdip. This would have resulted in raising the computed profile considerably at the highest point of the body and somewhat less at the northeastern end of the body whereas it would have been lowered at the northeastern end of the profile. At the center of the body the profile would have raised only slightly and farther southeast it would not have been affected appreciably. Inasmuch as the intrusion is concordant at the surface, however, it is likely that the northeastern contact continues steeply downward for at least several thousand feet at section *E–E′*.

The discrepancy between computed and measured magnetic profiles at their northeast ends is most reasonably explained by the complex outline of the South Mountain intrusion and its associated magnetic anomaly

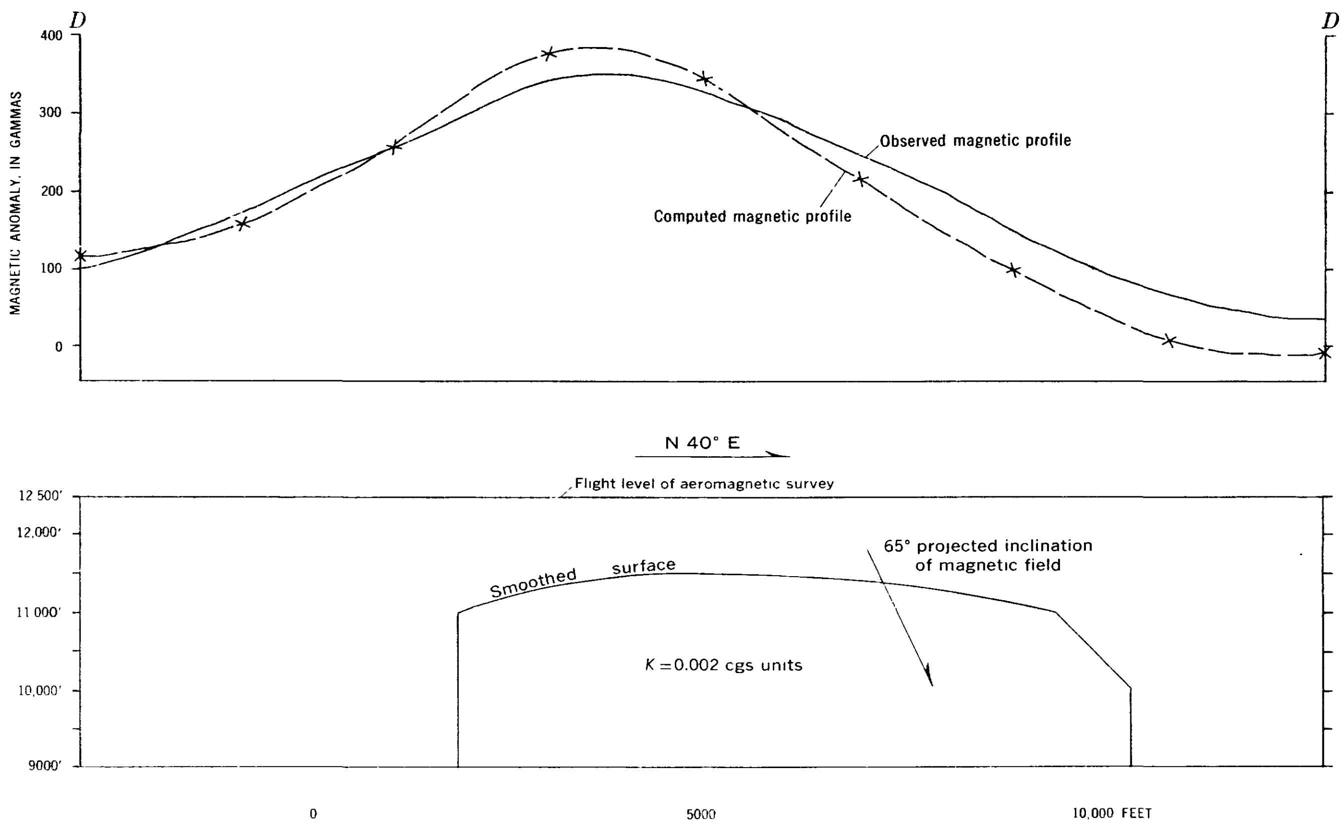

FIGURE 40.—A two-dimensional analysis of the North Mountain magnetic anomaly.

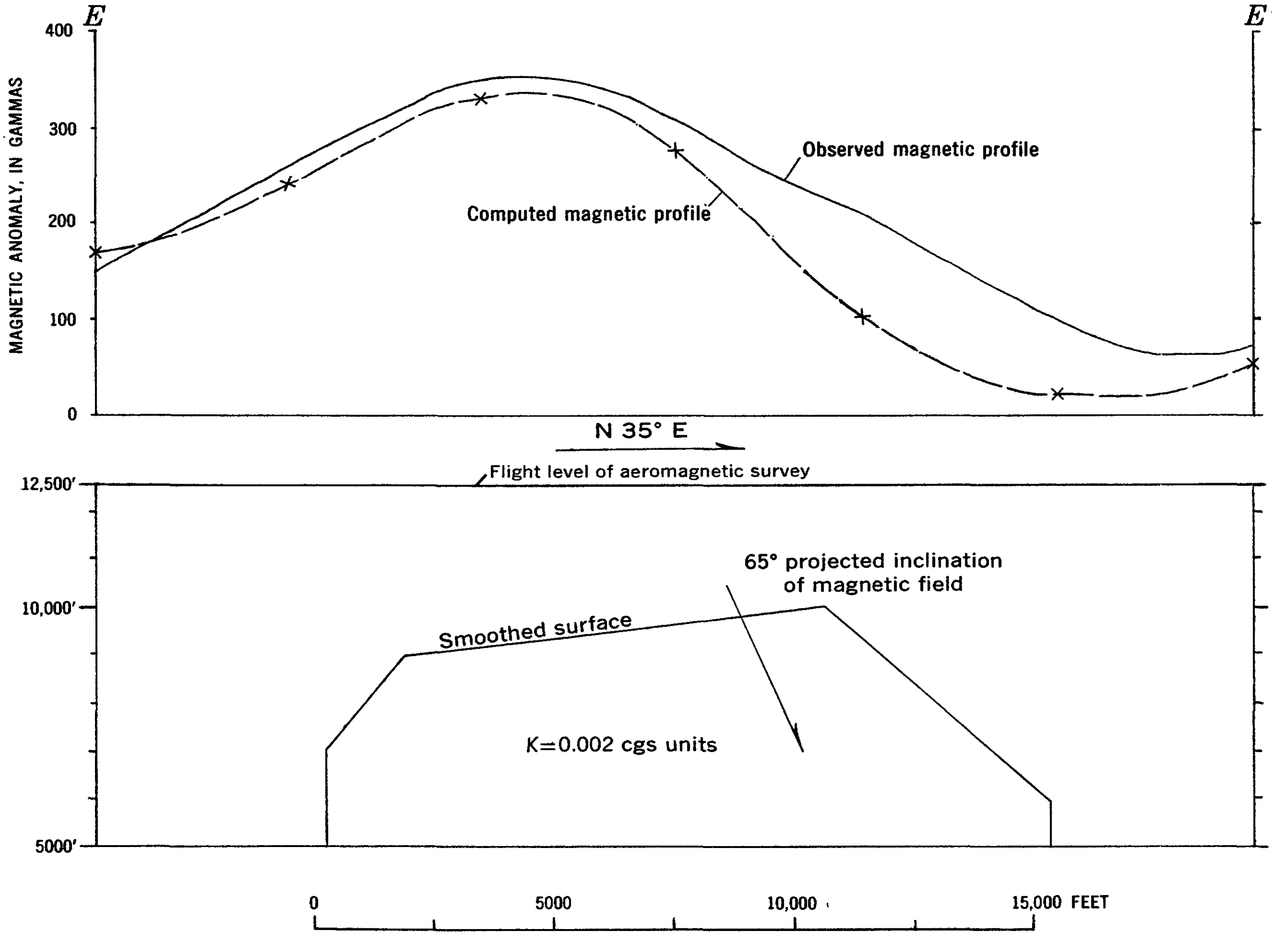

FIGURE 41.—A two-dimensional analysis of the South Mountain magnetic anomaly.

as shown on plates 14 and 16. Farther northwest, laccolithic intrusions continue a mile northeast of the igneous contact at section *E–E′*. They have influenced the magnetic profile along the northeastern part of *E–E′*, so that comparison with a geologic section along *E–E′* is not entirely valid and magnetic evidence cannot be in complete agreement. The broad basement low northeast of South Mountain may also contribute slightly to the discrepancy between measured and computed profiles.

The assumed intrusive mass shown in figure 41 ranges in thickness from about 4,000 feet at the southwest side to about 5,000 feet at the northeast side. Although the shape and dimensions only approximate those of the actual intrusion, the average thickness is unlikely to be less than that shown, if the assumed magnetic contrast is nearly correct.

No estimate of the thickness of the Middle Mountain laccoliths could be made because of their irregular shapes. The amplitude of their associated anomalies, however, suggests that they are thinner than the laccoliths at North and South Mountains. This qualitative estimate is in general agreement with that of Hunt (1958, p. 346). He estimates the maximum thickness of the Mounts Tukuhnikivatz and Peale laccoliths to be about 0.4 mile each, and the maximum thickness of the laccoliths at North and South Mountains to be about 0.6 and 0.5 mile, respectively. Comparisons of these estimates with those made from magnetic data are not entirely valid, however, as the latter give average thicknesses, and also take into account the effect of the central stocks, which extend much further downward.

GRAVITY ANOMALIES

The broad gravity high over the central and southern La Sal Mountains results from the combined effects of the laccolithic intrusions and the relatively shallow or dense basement rocks between the basement zones defined by the Wilson Mesa and Paradox Valley regional gradients. Gravity anomalies are apparently least influenced by basement rocks and salt anticlines in the area east and southeast of La Sal Pass; therefore the increase of about 6 milligals from the northeast corner of T. 28 S., R. 25 E. (Salt Lake meridian) west-

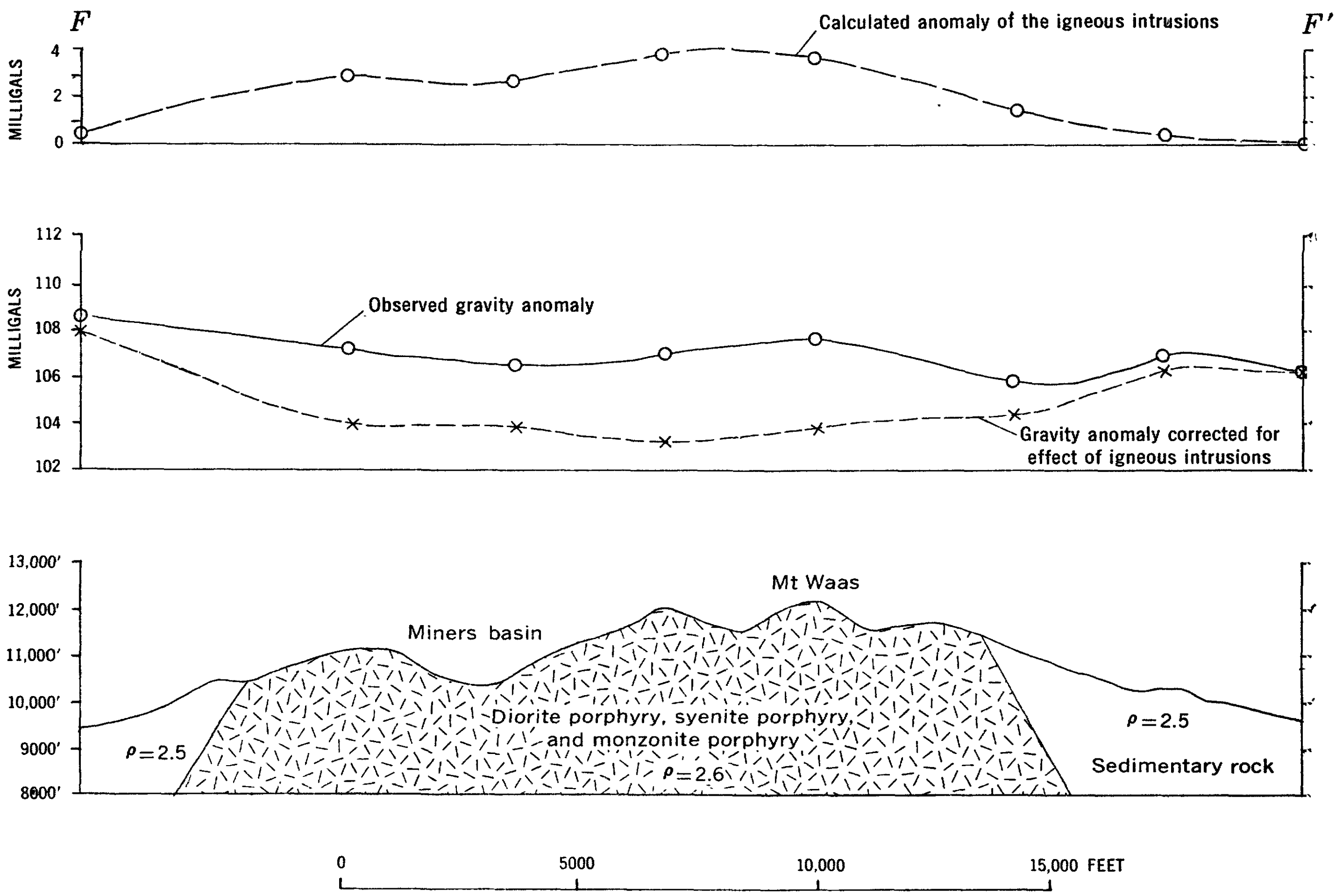

FIGURE 42.—A two-dimensional analysis of the gravity anomaly at North Mountain.

ward to La Sal Pass is probably largely related to the laccolithic intrusions.

GRAVITY ANOMALIES AT NORTH MOUNTAIN

Gravity anomalies of the igneous intrusions at North Mountain are nearly obscured by the Wilson Mesa and Paradox Valley regional gradients and by the gravity low at Castle Valley. In general, gravity values are much lower at North Mountain than at Middle Mountain, even though there is probably a much larger volume of igneous rock at North Mountain. The lower values are largely due to the influence of the Paradox Valley and Wilson Mesa regional gradients, but may also be related to thicker salt at North Mountain.

The Paradox Valley regional gradient parallels the northeast margin of North Mountain and is reinforced by the anomaly of the igneous intrusions. On the other hand, the Wilson Mesa regional gradient strikes northeast across the trend of the laccoliths in the northwestern part of the North Mountain. A pronounced negative indentation in the gravity contours near Horse Mountain indicates that thickened salt of the Castle Valley anticline extends beneath the laccoliths. If there were no salt beneath the northwestern laccoliths, there would probably be a positive anomaly in the contours of the Wilson Mesa regional gradient, because the laccoliths are more dense than the surrounding sedimentary rocks.

The existence of thickened salt beneath the northwestern laccoliths can be further demonstrated by subtracting from the gravity values the positive anomalies theoretically associated with the laccoliths. A simplified two-dimensional model of North Mountain is shown in figure 42. The base of the laccolithic intrusions is assumed to be at an elevation of 8,000 feet. The density contrast between the igneous intrusions and the adjacent sedimentary rocks is assumed to be +0.1 g per cm^3, which is consistent with the measured density of about 2.6 g per cm^3 of the igneous rocks and 2.5 g per cm^3 for the adjacent sedimentary rocks.

Near Mount Waas the calculated positive anomaly is about 3.8 milligals, and it falls off to zero at stations near the ends of the profile. When the calculated positive anomalies are subtracted from the observed gravity values, a gravity low of about 4 milligals is shown by the dashed line of figure 42. This low is attributed to the presence of thickened salt beneath the laccoliths. If the base of the laccoliths is lower than 8,000 feet, or if the presence of a central stock were considered, the calculated positive anomalies would be greater, and there would be correspondingly more salt thickening.

The gravity low at North Mountain does not appear to continue southeast of Mount Tomasaki, although additional gravity coverage might reveal a continuing low. If thickened salt does connect the Castle Valley salt anticline with the Paradox Valley salt anticline, it has no apparent gravitational effect for about 5 miles southeast of Manns Peak.

GRAVITY ANOMALIES AT MIDDLE AND SOUTH MOUNTAINS

Two small gravity highs are shown at Middle Mountain. The smaller high, north of Mount Tukuhnikivatz, is near the Middle Mountain stock (Hunt, 1958, pl. 39). The other is east of Mount Mellenthin in an area where there are no exposed igneous rocks. Because these anomalies are small, they may represent errors in the gravity anomalies resulting from errors in elevations or in terrain corrections.

SUMMARY OF CONCLUSIONS

Major structures of the basement are outlined by the steepened regional gravity gradients of Wilson Mesa and Spanish and Paradox Valleys. Closely analogous structures are indicated by regional magnetic anomalies. Whether these steepened gravity gradients and magnetic anomalies are related predominantly to basement faults or warps or to intrabasement contrasts in density and magnetization is unknown, but available well data in adjoining areas indicate that relatively large basement relief may contribute to these gradients.

Both the Paradox Valley regional gravity and magnetic gradients trend northwestward, parallel to the Paradox Valley salt anticline and to the northeast slope of North Mountain. These relations indicate that basement structure has localized the positions of the salt anticline, and of the stock and associated laccoliths at North Mountain.

From Pack Creek to North Mountain the Wilson Mesa regional gravity gradient trends northeastward, transverse to the structure of Triassic and younger beds, hence the source of the gradient is probably pre-Triassic in age. Similarly, magnetic contours trend northeastward in the vicinity of Wilson Mesa, indicating that the basement compositional or structural trends are northeast. Left-lateral offsets in the trends of the salt anticlines coincide approximately with the position of the transverse regional anomalies. If basement faults are represented by the steepened regional gradients along Paradox Valley and Wilson Mesa, then the laccoliths at North Mountain were emplaced near their intersection. Gravity evidence suggests that a northeastward-trending basement high extends from North Mountain past Beaver Mesa to the Dolores River, and magnetic contours strike generally northeast in the same area.

The steepened Spanish Valley regional gravity gradient has a westerly trend from Pack Creek to the west margin of the area, north of Kane Springs Canyon. Similarly, magnetic contours between La Sal and Kane Springs Canyon trend westward, so basement structural or compositional trends are probably westerly in the general region between Spanish Valley and Pack Creek and Kane Springs Canyon.

Near South Mountain, regional magnetic contours trend northwestward, parallel to the gravity low over the Pine Ridge salt anticline. As at North Mountain, the coincidence of magnetic trends with the Pine Ridge salt anticline and the laccolithic intrusions of South Mountain indicates that South Mountain was probably intruded into a salt anticline, the site of the salt anticline and the later intrusions being controlled by basement structure.

There is no apparent evidence for basement structural control of the stock and laccoliths at Middle Mountain.

The relatively small amplitude and large breadth of the regional magnetic anomalies suggest that their sources are generally deep throughout much of the area, and that they are largely due to changes of basement magnetization. Of special interest is the fact that the La Sal Mountains are in a broad, shallow regional magnetic low. This indicates that the basement rocks are comparatively nonmagnetic, and that any remaining magmatic source of the laccoliths lies at great depth.

The geophysical data, combined with well data from adjoining areas, indicate that the region beneath and south of the La Sal Mountains and Spanish Valley, and southwest of Paradox Valley, is underlain by relatively shallow basement rocks, or basement rocks of high density, whereas the region north of the La Sal Mountains, at Castle, Fisher, and Sinbad Valleys, is underlain by deeper basement rocks or basement rocks of lower density. The boundary between these basement zones coincides with the positions of the Wilson Mesa and Paradox and Spanish Valley regional gravity gradients. Such a separation of the basement into two areas of contrasting properties is not reflected in the structure of the Mesozoic beds, and it is therefore probably pre-Triassic in age. Because the sites of the salt anticlines of Paradox and Spanish Valleys were probably determined by faults or warps delimiting these two basement zones, they may have originated in late Paleozoic time, accompanying uplift of the ancestral Uncompahgre Range and the development of the Paradox basin. If this is so, these faults or warps may have influenced the depositional thickness of the Paradox salt; salt thickness may have been greater north of the boundary than south of it. It is also possible that the zone originated prior to late Paleozoic time and was subsequently rejuvenated during late Paleozoic deformation.

There is no geophysical evidence that basement structure controlled the positions of Castle Valley and Fisher Valley salt anticlines; magnetic contours and regional gravity contours are transverse to these anticlines. The site of Sinbad Valley salt anticline may have been controlled by basement structure, but the geophysical evidence is not strong.

The vertical amplitudes of the salt anticlines of the area are on the order of 7,000 to 10,000 feet, on the basis of analysis of their associated gravity anomalies. Thickened salt of the Castle Valley salt anticline extends under the laccoliths of North Mountain, but the extent of salt thickening or elevation of the base of the laccoliths cannot be determined from gravity data.

Correlation is generally good between magnetic anomalies and the positions of the igneous intrusions of the mountains. Analysis of the magnetic anomaly at North Mountain indicates that the average elevation of the base of the laccoliths in the southeastern part is about 9,000 feet, and it is probably lower under the central part. At South Mountain, the average elevation of the base of the laccoliths is estimated to be about 5,000 feet.

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