Regional Geophysical Investigations of the Lisbon Valley Area Utah and Colorado

By P. EDWARD BYERLY *and* H. R. JOESTING

GEOPHYSICAL FIELD INVESTIGATIONS

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CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

GEOPHYSICAL FIELD INVESTIGATIONS

REGIONAL GEOPHYSICAL INVESTIGATIONS OF THE LISBON VALLEY AREA, UTAH AND COLORADO

By P. Edward Byerly and H. R. Joesting

ABSTRACT

Aeromagnetic and gravity surveys have been conducted in the Lisbon Valley area as part of a study of the regional geology of the Colorado Plateau. The Lisbon Valley area is located in the Paradox Basin in the east-central part of the Colorado Plateau. As here defined it includes the southern three-quarters of the Mount Peale, Utah and Colorado, 30-minute quadrangle.

Exposed rocks range in age from Pennsylvanian to Quaternary, and include, in the northern part of the area, the intrusive rocks of the La Sal Mountains of probable Tertiary age. The Pennsylvanian section includes limestones and clastic rocks, whereas the overlying Permian and younger sedimentary rocks are mainly sandstone, siltstone, and shale. Evaporites of Pennsylvanian age have been penetrated in a well in the Lisbon Valley area. Older rocks of Pennsylvanian, Mississippian, Devonian, and Cambrian(?) age have been penetrated in wells drilled in adjoining areas, and probably are present in the Lisbon Valley area.

The major structure is the Lisbon Valley faulted salt anticline, with its accompanying negative gravity anomaly of about 15 milligals. This structure differs from most of the other large salt anticlines of the Paradox Basin, in that the evaporites do not intrude the overlying rocks. A piercement salt plug, north of the Lisbon Valley anticline, and local thickening of salt in the western and northwestern parts of the area are also indicated by gravity anomalies. The alinement of late Paleozoic salt intrusions with the South Mountain group of igneous intrusions in the La Sal Mountains indicates that this group was intruded along a zone of previous structural activity.

The magnetic anomalies are caused mainly by variations in the magnetization of the basement rocks. Basement structural trends, as indicated by magnetic trends, coincide in part with surface structure and are divergent in part. A prominent basement ridge or platform in the southwestern part of the area, flanked by a basin to the northeast, is indicated by the magnetic data.

INTRODUCTION

Aeromagnetic and gravity surveys have been conducted in the Lisbon Valley area of southeast Utah with the aim of providing information on the regional geology—in particular, on those aspects which may not be apparent from surface evidence alone. More complete information on the geologic structure might aid in revealing any possible relationship between structure and the localization of uranium deposits.

The Lisbon Valley area, as here defined, includes the southern three-quarters of the Mount Peale, Utah and Colorado, 30-minute quadrangle, which adjoins the Paradox Valley 30-minute quadrangle of southwest Colorado. Gravity and aeromagnetic surveys of the Uravan area, which includes the latter quadrangle, have been discussed in a previous publication (Joesting and Byerly, 1959). The location of the Lisbon Valley and Uravan areas is shown in figure 17.

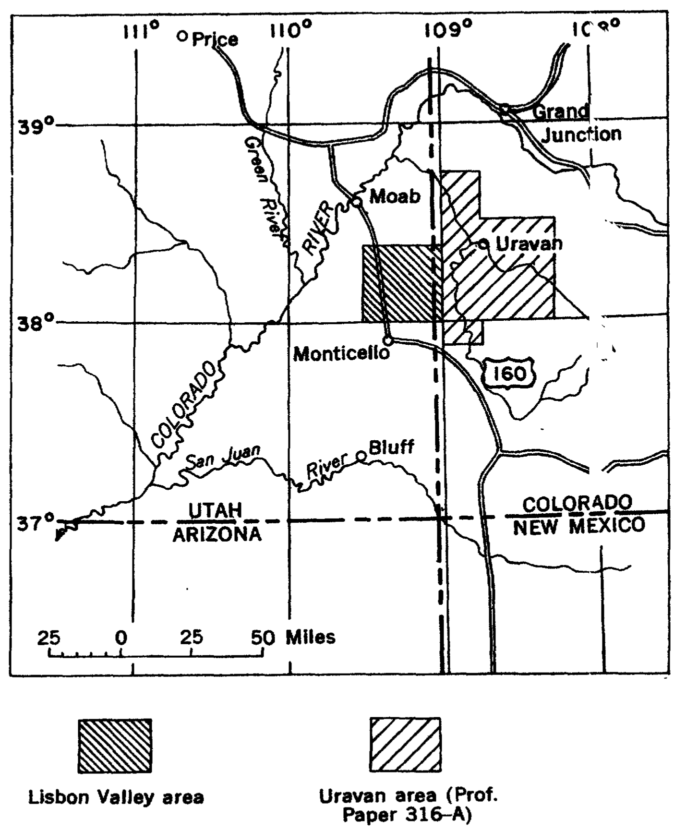


Figure 17.—Index map showing location of the Lisbon Valley and Uravan areas.

ACKNOWLEDGMENTS

The authors are grateful for the interest and advice of many geologists of the U.S. Geological Survey and the Atomic Energy Commission who have worked on related problems on the Colorado Plateau. Information on the geologic structure and stratigraphy of the area was supplied by W. D. Carter and G. W. Weir, of the Geological Survey. Roland Henderson and Isidore Zietz, also of the Survey, assisted on magnetic interpretation. Winthrop Means, James Case, and C. H. McCurdy assisted on the gravity survey; the Bouguer anomalies were computed by Eugene Tassone.

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

GEOLOGY

Since sedimentary rocks are, with rare exception, virtually nonmagnetic, density is the most important physical property of these rocks involved in the interpretation of the geophysical maps presented here. Consequently, in the section on sedimentary rocks, emphasis is placed on groups of rocks with apparently similar densities.

SEDIMENTARY ROCKS AND THEIR DENSITIES

The stratigraphic sequence exposed in the Lisbon Valley area is shown in the table below. The thicknesses of the formations are based on the exposed section around the Lisbon Valley anticline and on diamond-drilling data (Lekas and Dahl, 1956, p. 163). The absence of the Moenkopi formation of Triassic age on the crest of the anticline and the history of late Paleozoic salt movement in this general area suggest that the Cutler and Moenkopi formations may vary appreciably in thickness over the Lisbon Valley area.

Stratigraphic sequence exposed in the Lisbon Valley area

[Data from Lekas and Dahl (1956), Weir and Dodson (1958), and G. W. Weir (written communication)]

System	Group or formation	Thickness (feet)	Lithologic character
Quaternary		100±	Gravels flanking La Sal Mountains.
	———Unconformity———		
Cretaceous	Mancos shale, Dakota sandstone, and Burro Canyon formation.	500±	Marine shale (Mancos), sandstone, conglomerate.
Jurassic	Morrison formation (Brushy Basin shale member, Salt Wash sandstone member).	700–800	Shale and bentonitic mudstone; interbedded sandstone and mudstone.
	San Rafael group: Summerville formation Entrada sandstone Carmel formation.	250–500	Interbedded sandstone and mudstone; massive sandstone.
	———Unconformity———		
Jurassic and Triassic	Glen Canyon group: Navajo sandstone Kayenta formation Wingate sandstone.	680±–910±	Massive and irregularly bedded sandstone.
Triassic	Chinle formation	340–480	Sandstone, mudstone, and shale.
	———Unconformity———		
	Moenkopi formation	0–280±	Siltstone; absent on crest of Lisbon Valley anticline.
	———Local Unconformity?———		
Permian and Pennsylvanian	Cutler and Rico formations (undifferentiated).	1470	Arkosic and quartzose sandstone, and siltstone.
Pennsylvanian	Hermosa formation		Upper member: Limestone, sandstone, and shale. Paradox member: Salt, gypsum, anhydrite, black shale, and limestone; not exposed but penetrated by drill.

PRE-HERMOSA FORMATIONS

The sequence shown in the table is presumably underlain by sedimentary rocks of Pennsylvanian and pre-Pennsylvanian age. No wells have been drilled through the Hermosa formation in this area, but older rocks of Pennsylvanian, Mississippian, Devonian, and Cambrian(?) age have been penetrated by the drill in adjoining areas. The Gulf Oil Hart Point Federal 1, drilled in sec. 8, T. 31 S., R. 22 E., near the southwest edge of the area discussed in this report, penetrated Mississippian and Devonian rocks. Although little direct evidence is available concerning the densities of the pre-Hermosa rocks, they are probably well indurated and include a high proportion of carbonate rocks.

Consequently, there is probably little density contrast between the pre-Hermosa section and the average basement rocks.

HERMOSA FORMATION

The Paradox member of the Pennsylvanian Hermosa formation consists of cyclic deposits of salt, gypsum, anhydrite, black shale, and limestone. The salt and gypsum provide the major density contrasts within the sedimentary section in this area. The densities of the minerals halite and gypsum are about 2.14 and 2.31–2.33 g per cm^3 (grams per cubic centimeter), respectively (Birch, and others, 1942, p. 10). In contrast, the average density of the pre-Paradox sedimentary rocks is probably at least 2.6 g per cm^3.

The upper, or limestone, member of the Hermosa formation consists of thin to massive limestones interbedded with shales and sandstones. The density of this member is about 2.6 g per cm^3. An average effective density of 2.62 g per cm^3 was determined by weighting the thicknesses of sandstone and shale and of limestone, in driller's logs of this formation in the Moab area (Baker, 1933, p. 85–92), with the densities 2.55 and 2.65, respectively. The former density is approximately a 50-percent-saturated density for sandstones of the overlying Cutler formation (see below). This density may be somewhat high for the sandstones alone, but the density of shales generally increases more markedly with depth than does that of sandstones. The density of the limestone is based upon 8 samples from a measured section on the west side of Lisbon Valley.

RICO AND CUTLER FORMATIONS

Overlying the Hermosa formation are the arkosic and quartzose sandstones of the Rico and Cutler formations. The Cutler sandstones are the finer grained equivalents of Permian granite wash along the west front of the Uncompahgre Plateau, about 25 to 30 miles to the east. The dry and wet densities of 30 well-cemented surface samples of finer grained Cutler sandstones from the vicinity of Gateway, Colo., averaged 2.50 and 2.58 g per cm^3, respectively. The saturated densities were determined without placing the samples in a vacuum, and therefore may be a little low. Thus, a 50-percent-saturated density for these rocks is probably about 2.55 g per cm^3.

MESOZOIC FORMATIONS

Overlying the Cutler formation is a thick section of Mesozoic sandstones and shales (see table). The density of the section from the Wingate sandstone to the Salt Wash sandstone member of the Morrison formation in the vicinity of Uravan, Colo., was determined gravimetrically to be about 2.50 g per cm^3 (Joesting and Byerly, 1959, p. 5).

CRYSTALLINE ROCKS AND THEIR MAGNETIC SUSCEPTIBILITIES

Precambrian basement rocks are not exposed in the Lisbon Valley area, except as xenoliths in the laccolithic complex of the La Sal Mountains. The few undoubted xenoliths found in the stocks and laccoliths of the Henry and La Sal Mountains are largely mica schist, granite, granite gneiss, and pegmatite. Most of the inclusions found are hornblende-rich rocks of uncertain origin (Shoemaker, 1956, p. 54). The crystalline rocks exposed in the Uncompahgre Plateau to the east are largely quartzose schists, gneisses, and granites. The few measurements of magnetic susceptibility available for rocks of the Uncompahgre Plateau suggest that these rocks are, in general, of low to intermediate susceptibility.

The magnetic susceptibilities of 29 samples (measurements by William Huff, U.S. Geological Survey) from the post-Mancos stocks and laccoliths of the La Sal Mountains range from 0.005×10^{-3} to 3.21×10^{-3} cgs units. Nine of the samples have susceptibilities less than 0.1×10^{-3}, whereas 10 samples have susceptibilities greater than 2.0×10^{-3}. The low values may be the result of weathering or possibly deuteric alteration. The remanent magnetization of the samples is erratic in direction and generally of about the same magnitude as the induced magnetization.

STRUCTURE

The major geologic structure of the area is the faulted anticline underlying Lisbon Valley (pl. 6). A negative gravity anomaly of the order of 15 milligals is centered over the structure (pl. 7). The core of the structure is composed of evaporites of the Paradox member of the Hermosa formation. The Lisbon Dome 1 of the Union Oil Co. of California, drilled in 1927 on the crest of the structure, penetrated salt of a depth of 1,620 feet, and an additional 3,390 feet at Paradox, including about 2,600 feet of salt, 600 feet of limestone and limy shale, and 150 feet of shale (Baker, 1933, p. 92).

The Lisbon Valley anticline differs from most of the other large salt anticlines in the Colorado Plateau in that the evaporites are not intrusive into the overlying sedimentary rocks. The following description of the structure of the anticline is taken from Lekas and Dahl (1956, p. 162).

> The anticline is asymmetrical with the southwest flank dipping 8°, on the Chinle-Cutler contact, away from the Lisbon Valley fault which lies along the axis of the anticline. The downthrown northeast side of the anticline dips 6° into the

Disappointment syncline. Maximum throw along the fault is 4,000 feet with displacement decreasing rapidly toward the noses of anticline. The dip of the fault plane in the Big Indian mine is 58° northeast. The fault generally is confined to a single plane near the center of the anticline, but toward the noses it divides into several branches.

The name "Disappointment syncline," as used in this quotation, has been changed to East Coyote syncline in recent mapping (W. D. Carter and J. L. Gualtieri, 1957a, b). The latter name is used on plate 6.

The Lisbon Valley anticline lies on the same structural trend as the Dolores anticline to the southeast (fig. 18). It is flanked on the northeast by the East Coyote syncline. Photogeologic maps of the area indicate that this syncline plunges in both directions toward a structural minimum at the northwest end of Island Mesa. The southwest dips on the northeast flank of East Coyote syncline continue as far as Pine Ridge (pl. 6). Exposures of the Burro Canyon and Dakota formations along the north edge of the valley of La Sal Creek show that the beds dip northeasterly and are undisturbed (W. D. Carter, written communication, 1957). As will be shown, the reversal of dip in the La Sal Creek Valley area is related to a salt plug which underlies the valley.

The broad Hatch Rock syncline lies to the west of the Lisbon Valley anticline, in the western part of the Dry Valley area. South of the Lisbon Valley anticline the flanking dips decrease and grade into gentle regional dips in a southerly direction. (See pl. 6.)

The intrusive rocks of the South Mountain group of the La Sal Mountains laccolithic complex are exposed

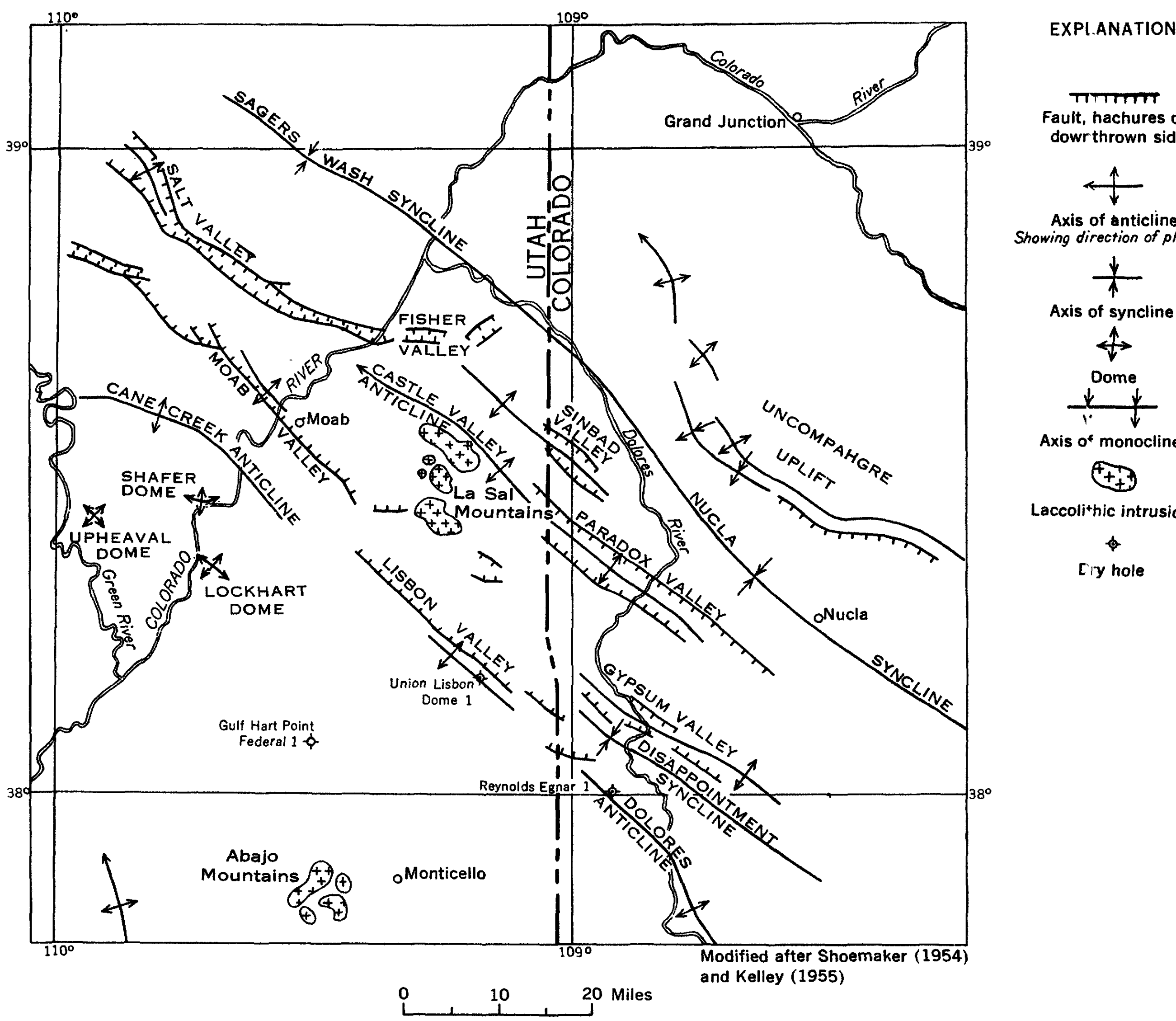


FIGURE 18.—Major geologic structures in the salt anticline region of southwest Colorado and southeast Utah.

at the north-central edge of the area. Steeply dipping hogbacks flank the intrusions (pl. 6).

AEROMAGNETIC SURVEY

Airborne magnetic surveys of the Lisbon Valley area and the adjoining Uravan area in Colorado were made in 1952 by the Geological Survey, concurrently with airborne radioactivity surveys of parts of the Colorado Plateau. The magnetic data were subsequently compiled and used in this paper.

The magnetic measurements were made by a continuously recording AN/ASQ-3A magnetometer, installed in a 2-engine airplane flying at 150 miles per hour. East-west traverses were flown about 2 miles apart, at a height of about 500 feet above the ground. Photomosaics were used for pilot guidance, and the flight path of the plane was recorded by a gyrostabilized continuous-strip camera. The distance from plane to ground was measured with a continuously recording radar altimeter. The magnetic data were plotted and a contour map constructed on photomosaics. The magnetic map (pl. 8) used in this report was made by adjusting the photomosaic map to the topographic map which subsequently became available. The flying and compilation were under the direction of J. L. Meuschke.

Because of operational limitations, the accuracy of the magnetic map is somewhat lower than that desirable for theoretical analysis. The accuracy of the measurements as affected by positioning was reduced over rough terrain by the requirement that to measure radioactivity the plane fly at a height of about 500 feet above the ground rather than at a constant barometric level. The necessity of using semicontrolled photomosaics, because suitable topographic maps were not available at the time, has also resulted in positional errors. In addition, the 2-mile spacing of flight lines, though adequate for the broader magnetic features, is not sufficiently close to outline accurately the smaller, higher gradient anomalies. For these reasons, estimates of depths to sources of anomalies are subject to somewhat more than the usual uncertainty.

GRAVIMETRIC SURVEY

The gravimetric survey was conducted during the summer of 1955 and part of the summer of 1956. A total of 401 stations was established in 1955 and an additional 94 stations in 1956. Surveying was done with a Worden gravimeter with a scale constant of about 0.5 milligal per division.

METHOD OF SURVEY

Base stations for the survey were established by the "three-step" looping technique (Nettleton, 1940, p. 38–39), involving measurements at stations A, B, C, D, etc., in the order A, B, A, B, C, B, C, D, etc. Additional stations were tied to this base network with, in most cases, a lapse of but a few hours between measurements at base stations.

The survey was tied to four base stations on base lines between La Sal Junction, Utah, and Paradox, Colo., and between La Sal Junction, Utah, and Monticello, Utah. These base stations are tied to the pendulum station of the U.S. Coast and Geodetic Survey designated "Egnar" near Egnar, Colo.

ELEVATIONS

Elevation control for the gravity stations was provided by bench marks of the U.S. Coast and Geodetic Survey, elevations of triangulation stations of the U.S. Atomic Energy Commission net in the Lisbon Valley area, vertical angle bench marks and photogrammetric spot elevations from topographic maps of the U.S. Geological Survey, and by altimetry. The altimetric elevations were determined largely by the single-base method. Some were determined by three-step looping and a few by the "leap-frog" technique, involving a moving base altimeter. A small number of elevations were determined with roving altimeters, with intermediate ties to points of known elevation.

BOUGUER ANOMALIES

The Bouguer anomalies were computed with an elevation factor of 0.062 milligal per foot, corresponding to a density in the Bouguer correction of 2.50 g per cm^3. The anomalies were reduced to sea level and the international gravity formula of 1930 was employed in the reduction. Three hundred milligals was added to the anomaly at each station so that all values would be positive.

Terrain corrections were made for 175 stations. The corrections were generally carried out to, and including, zone *J* of Hammer's tables (Hammer, 1939), a distance of about 4 miles from the station.

ACCURACY OF THE BOUGUER ANOMALIES

The principal factor affecting the accuracy of the anomalies is the accuracy of the elevations. Careful altimetric checks of the differences in elevation between certain photoalidade, phototrig, and multiplex spot elevations, agreed with the photogrammetric differences to within less than 5 feet. Checks were made on differences up to 300 feet. We believe that many of the station elevations are accurate to within 5 feet, and that most are accurate to within 10 feet.

Estimates of the errors affecting the difference in the Bouguer anomaly between two stations in the same local area are listed below:

Source	*Estimated error (milligal)*
Observed gravity	0–0.1
Elevation	0–0.6 (0–10 ft)
Latitude correction	0–0.1
Terrain correction	Generally small where made.

The terrain correction out to zone *J* of Hammer's tables (Hammer, 1939) in areas where the correction was not made, is generally less than 0.5 milligal. Residual terrain effects vary more or less smoothly over the area and probably have little relative influence on individual anomalies. From a consideration of the errors listed above, it is probable that over most of the area in which the contours are shown by solid lines on plate 7 the difference in the Bouguer anomaly between 2 stations within reasonable proximity of one another is accurate to about 1 milligal.

MAGNETIC MAP

The anomalies and trends shown on the magnetic map (pl. 8) are related predominantly to variations in the magnetization and to structural alinements of the basement complex and only to a minor extent to irregularities in the surface of the basement. The sedimentary rocks in the area are virtually nonmagnetic, and except in the extreme northern part of the area, they contain no known intrusions of igneous rock.

Three distinct magnetic patterns are evident on plate 8. To the east and northeast, near Island Mesa and Wray Mesa, the magnetic map is characterized by anomalies of comparatively low gradient trending northwesterly. Near Peters and East Canyons, to the southwest, a group of relatively high-gradient nonlinear anomalies is imposed on a generally east-west regional trend. In the Hatch Wash-La Sal area to the northwest and west, a west-plunging trough dominates the magnetic map.

EASTERN PART OF THE AREA

The comparatively low magnetic gradients in the eastern part of the area reflect the increasing depth to the basement in a northeasterly direction toward the axis of the Paradox Basin. Their northwesterly trend suggests a corresponding structural trend in the basement, generally parallel to the major structural trends of the overlying sedimentary rocks. These are, in general, similar to the major magnetic and structural trends in the Uravan area, which adjoins the Lisbon Valley area on the east (Joesting and Byerly, 1959).

The broad magnetic high centered near the NE cor. T. 30 S., R. 25 E., near the eastern border of the area, is probably related to slight variations in the magnetization of the basement rocks. To produce the anomaly by basement topography alone would require either an improbably great relief on the surface of the basement or an unusually high magnetic susceptibility of the basement rocks. Computations following the method of Vacquier and others (1951) yield a depth of about 10,000 feet, or about 3,500 to 4,000 feet below sea level. A moderate susceptibility contrast in the basement rocks (of the order of 0.001 cgs units) is indicated. These are rough estimates, because the anomaly is not favorably suited to estimates of depth.

The magnetic high beginning just southeast of Island Mesa and the trough crossing Coyote Wash, both along the eastern border of the Lisbon Valley area, are northwestward continuations of important linear anomalies in the Uravan area. Analysis of these anomalies by the method of Vacquier and others (1951) yields depths of about 6,000 to 7,000 feet below the surface, or about sea level, under the Disappointment syncline in the Uravan area (fig. 18). The anomalies can also be reproduced by dipping dikelike bodies, with a variable and comparatively high polarization, at a depth of the order of 10,000 feet, or about 4,000 feet below sea level (Joesting and Byerly, 1959, p. 11). On the basis of estimates of the thickness of early Paleozoic formations by Cooper (1955, p. 59–65) the Precambrian basement is estimated to be about 4,000 feet below sea level at Reynolds Egnar 1 (fig. 18), which was bottomed in the Leadville limestone of Mississippian age 3,011 feet below sea level. The basement elevation of about 4,000 feet below sea level is thus in line with the depth estimate for the anomaly near the NE cor. T. 30 S., R. 25 E.

PETERS CANYON-EAST CANYON AREA

In the Peters Canyon-East Canyon area the east-west magnetic trends apparently reflect a corresponding east-west regional trend in the basement rocks, in contrast to the generally northwest trends in the sedimentary rocks. Several high-gradient nonlinear anomalies are imposed on the regional trend. These are evidently caused by variations in the magnetization and composition of the basement rocks. An alternative cause—large masses of igneous rocks intruded into the sediments—is considered unlikely. There is no structural evidence in the lowermost exposed formations—the Navajo sandstone of Jurassic and Jurassic(?) age, the

Entrada sandstone of Jurassic age, and the Wingate sandstone of Triassic age—of buried igneous intrusions. Consequently, any such intrusions would be pre-Wingate in age, but none of early Mesozoic or Paleozoic age are known on the Colorado Plateau.

Estimates of depths to the sources of the magnetic highs yield relatively small values. The composite high west of Peters Canyon (pl. 8) yields depth values ranging between about 5,000 and 5,500 feet beneath the surface, or between about 1,200 and 700 feet above sea level. The estimated depth to the source of the smaller anomaly at East Canyon Wash is about 6,500 feet beneath the surface, or about 600 feet above sea level. Moderate susceptibility contrasts, on the order of 0.001 cgs units, are indicated by both anomalies.

These estimates of depth are probably subject to more than the usual uncertainties, because the data are not so precise or so detailed as is desirable (p. 43). However, it seems likely that the depth to the basement under these anomalies is several thousand feet less than to the east and northeast.

Thus, the depth measurements indicate a comparatively shallow magnetically diverse basement in the south and southwestern part of the area, bordered by a deeper basin to the northeast. The basement relief may be due to regional dip of the basement surface, or to a combination of this and local structural or erosional relief, with a resultant basement ridge. As there is no surface evidence of such a feature, it would of necessity be pre-Wingate in age, or older than the oldest exposed rocks in the vicinity.

HATCH WASH-LA SAL AREA

In the northwestern part of the Lisbon Valley area, in the vicinity of Hatch Wash and the town of La Sal, the magnetic pattern is dominated by a prominent west-plunging trough. The southern extremity of this trough apparently defines the approximate boundary of the possible basement ridge already discussed. The sharply rising flanks of the trough and the change from west-northwest- to west-striking magnetic trends apparently represent corresponding changes in structural and compositional trends in the basement.

GRAVITY MAP

The contouring at the east edge of the Bouguer anomaly map (pl. 7) is based in part upon the gravity data of the survey of the Uravan area (Joesting and Byerly, 1959). The contouring at the west edge of the map was guided by unpublished gravity data from a 1956 survey of part of the Carlisle quadrangle to the west.

AREA SOUTHWEST OF THE LISBON VALLEY ANTICLINE

An examination of the Bouguer anomaly and aeromagnetic maps (pls. 7, 8) reveals a close correlation between the gravity nose crossing East Canyon Wash and the corresponding magnetic anomaly. Similarly, the flexures in the Bouguer anomaly contours just north and northwest of Peters Canyon show a correlation with the magnetic highs in this area. Evidently the broad gravity high in the southwest corner of the area is not associated with a corresponding magnetic anomaly. The change in trend of the surface structure in the vicinity of this high (pl. 9) suggests either some local withdrawal of salt or possibly some basement relief. The correlation of the magnetic and gravity anomalies suggests a zone of pre-Wingate intrusions and other basement structure trending roughly east-west in this area, as noted in the discussion of the magnetic map.

AREA WEST OF THE LISBON VALLEY ANTICLINE

A pronounced correlation exists between the Bouguer anomaly contours and the surface structure in the Dry Valley and Hatch Wash areas (pl. 9). The shape of the Hatch Rock syncline is apparently due in part to the migration of salt in easterly and northerly directions into the Lisbon Valley anticline and its northwestward extension. The structural depression northeast of the intersection of Hatch Wash and U.S. Highway 160 and the nose just north of this depression are unquestionably due to northward migration of salt into this nose whose axis lies about a mile and a half southwest of the Lisbon Valley fault. West of this nose the axis of the gravity minimum is offset to the south of the axis of the northwestward extension of the Lisbon Valley anticline. The axes of the gravity minimum and structural maximum come into coincidence again where they cross Hatch Wash. The discordance of these trends may be a consequence of thickening of salt due to flowage along somewhat different trends during Cutler time and (or) early Triassic time, or to depositional variations in thickness of salt. A thickening of salt along the trend of the gravity minimum of about 500 to 1,000 feet, with corresponding thinning or cutting out of the overlying Cutler and Triassic beds, would produce negative gravity anomalies of about 1 to 2.5 milligals. The flowage of sale during Moenkopi time in the Lisbon Valley area is shown by the absence of the Moenkopi on the crest of the Lisbon Valley anticline (Lekas and Dahl, 1956, p. 162).

The flexure in the structure contour lines in the Dry Valley area (pl. 9) is associated with a corresponding flexure in the Bouger anomaly contour lines. This could be the result of salt flowage into the area underlying the local embayment in the Bouguer anomaly contours, salt flowage in an easterly direction from the area just north, or a combination of both. The terrace in the Bouguer anomaly contour lines near point *A* on section *A–A′* of plate 7 may also be due to a local withdrawal of salt. Thus, the embayment extending in a southwesterly to westerly direction away from the gravity minimum in Lisbon Valley probably is the result of thickening of salt due to flowage. Lack of knowledge of the regional background due to other density contrasts complicates the problem, but it seems that this embayment in the Bouguer anomaly contours is more than can be explained by the existing surface structure. It is likely that there is local thinning of the Cutler and (or) Triassic formations due to the migration of salt before its main movement in post-Mancos time.

LISBON VALLEY ANTICLINE

The dip of the Lisbon Valley fault at the Big Indian mine, near the northern end of the Lisbon Valley anticline (pl. 6), is 58° NE. (Lekas and Dahl, 1956, p. 162). The surface dips of the sedimentary rocks on the southeast flank of the structure are on the order of 20° or less. From these data on the structure, the gravity anomaly centering over the Lisbon Valley anticline is rather broader than might be expected.

Two calculated anomalies, with the density distribution employed, are shown in figures 19 and 20. Figure 19 shows the calculated effect of the salt core. This three-dimensional calculation was made with the aid of the tables for calculating the effects of arbitrarily shaped masses of Cassinis, Dore, and Ballarin (1937). The density contrast (-0.375 g per cm^3) used in the computation is the average of the density contrasts -0.4 and -0.35 g per cm^3. This is not intended to imply that the density contrast is known to two or three significant figures. Figure 20 shows the effect of a two-dimensional mass distribution. The calculated anomaly is that due to the density contrasts on the southwest side of the fault and above the lower dashed line.

The contour lines on top of the salt in figure 19 are based upon the structure shown in figure 20 and a structure contour map on the top of the Cutler formation (Lekas and Dahl, 1956, fig. 3). The structure in figure 20 is based upon the depth to the top of the salt in Lisbon Dome 1 of the Union Oil Co. of California, the surface dips and outcrop widths from photogeologic maps of the U.S. Geological Survey (Hackman, 1952, 1956 a-f; Hackman and Tolbert, 1956; Tolbert, 1952, 1957 a-c), and the assumed thicknesses of beds younger than the Paradox evaporites on the flanks of the structure, as shown. The trend of the contour lines in figure 19 parallels the trend of the contour lines on top of the Cutler formation (Lekas and Dahl, op. cit.).

The two- and three-dimensional anomalies differ by little. This means that the decrease in structural relief toward either end of the anticline is not abrupt enough to invalidate a two-dimensional calculation across the center of the structure.

The density contrasts employed are probably as large as they can reasonably be expected to be. The calculated anomaly due to the anticline is about -13 milligals. However, the broad anomaly centering on Lisbon Valley is of the order of -18 milligals.

The residual anomaly remaining after removal of the calculated effect of the salt is probably due to several causes. Among these are the regional gradient on the southwest side of the Lisbon Valley fault, the downdropping and probably some thinning of the section younger than the evaporites on the northeast side of the fault, and increasing depth to the basement in a northeasterly direction. These effects cannot be separated from one another.

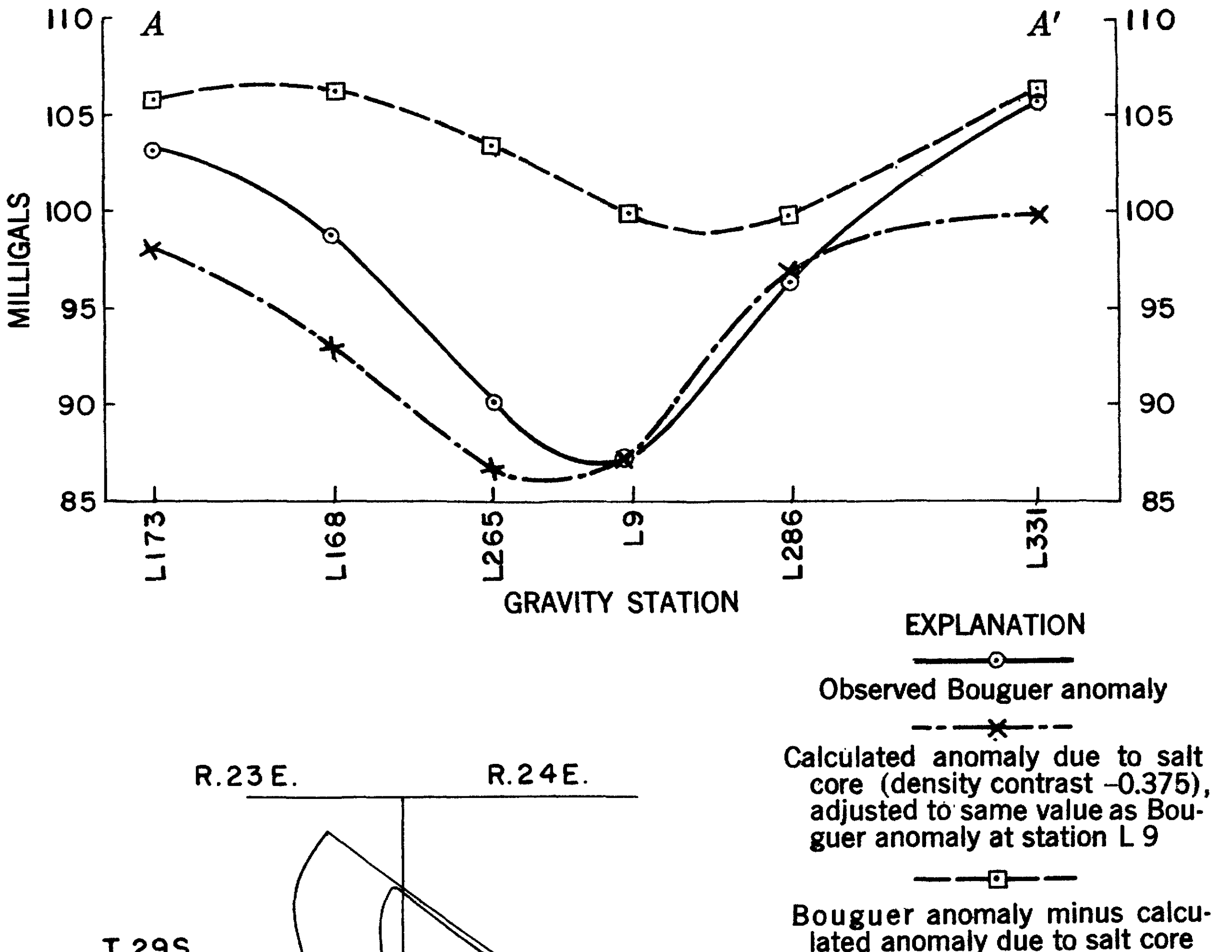
At its northern end, the Lisbon Valley anomaly divides into two parts: the northerly extension of the main anomaly and the nose north of the structural depression near Hatch Wash. The axis of the northerly extension of the main anomaly crosses the Lisbon Valley fault and lies just northeast of the fault. This may be due in part to relatively low dip of the fault and northeastward migration of the axis of the salt core with increasing depth of burial. However, the symmetry of the anomaly suggests that the salt intrusion is more or less symmetrical in cross section in this area, with thickened salt on the northeast side of the fault. Since the surface structure (pl. 6) does not reflect such thickening, it is likely that there is a thinning of the Cutler and Moenkopi formations on the northeast side of the fault.

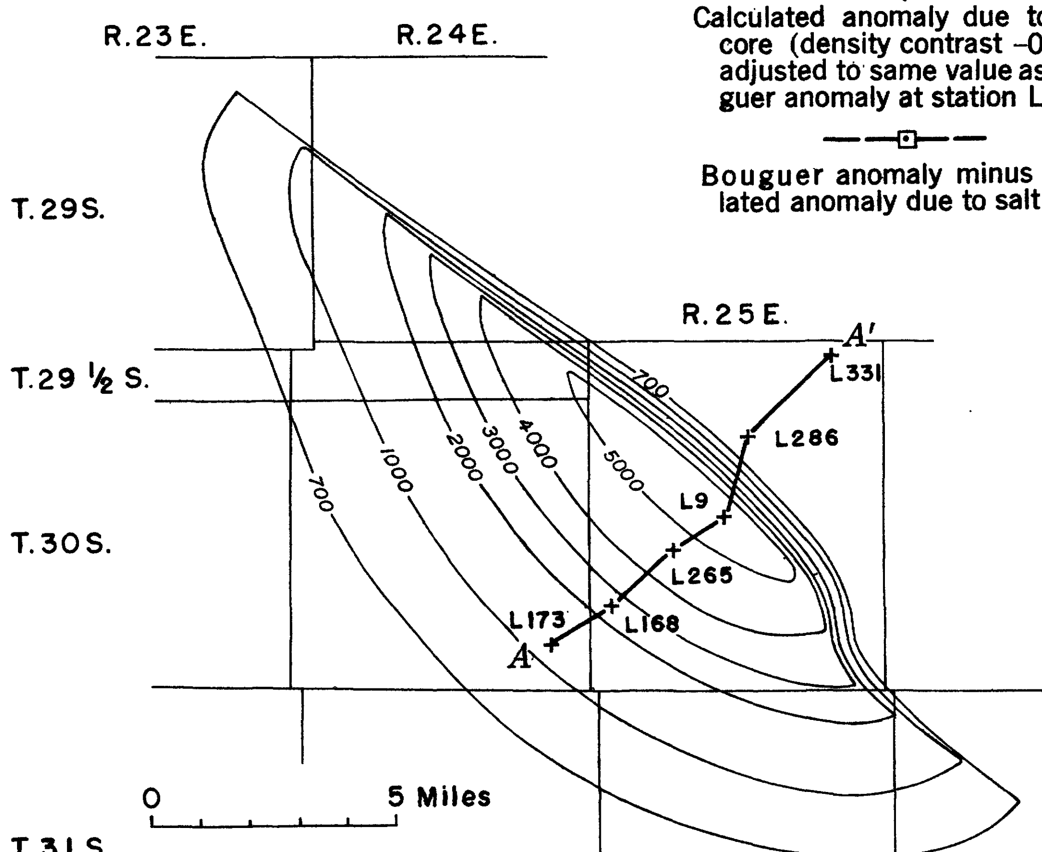
At the southern end, the axis of the Lisbon Valley anomaly diverges from the zone of faulting (pl. 6) and dies out in a southerly direction. This presumably is in large part due to the thinning of salt in this direction, but this cannot be said with certainty, because the local effect of intrabasement density contrasts is not clear.

The gravity minimum over Lisbon Valley centers south of the structural high as determined from photogeologic maps. The reason for this is uncertain, but it could be due to local depositional thickening of salt.

AREA EAST OF LISBON VALLEY

The correlation between East Coyote syncline and the anomaly pattern is not especially good. East of





Structure contours drawn on top of salt and gravity stations employed in three-dimensional analysis

FIGURE 19.—A three-dimensional analysis of the Lisbon Valley gravity anomaly.

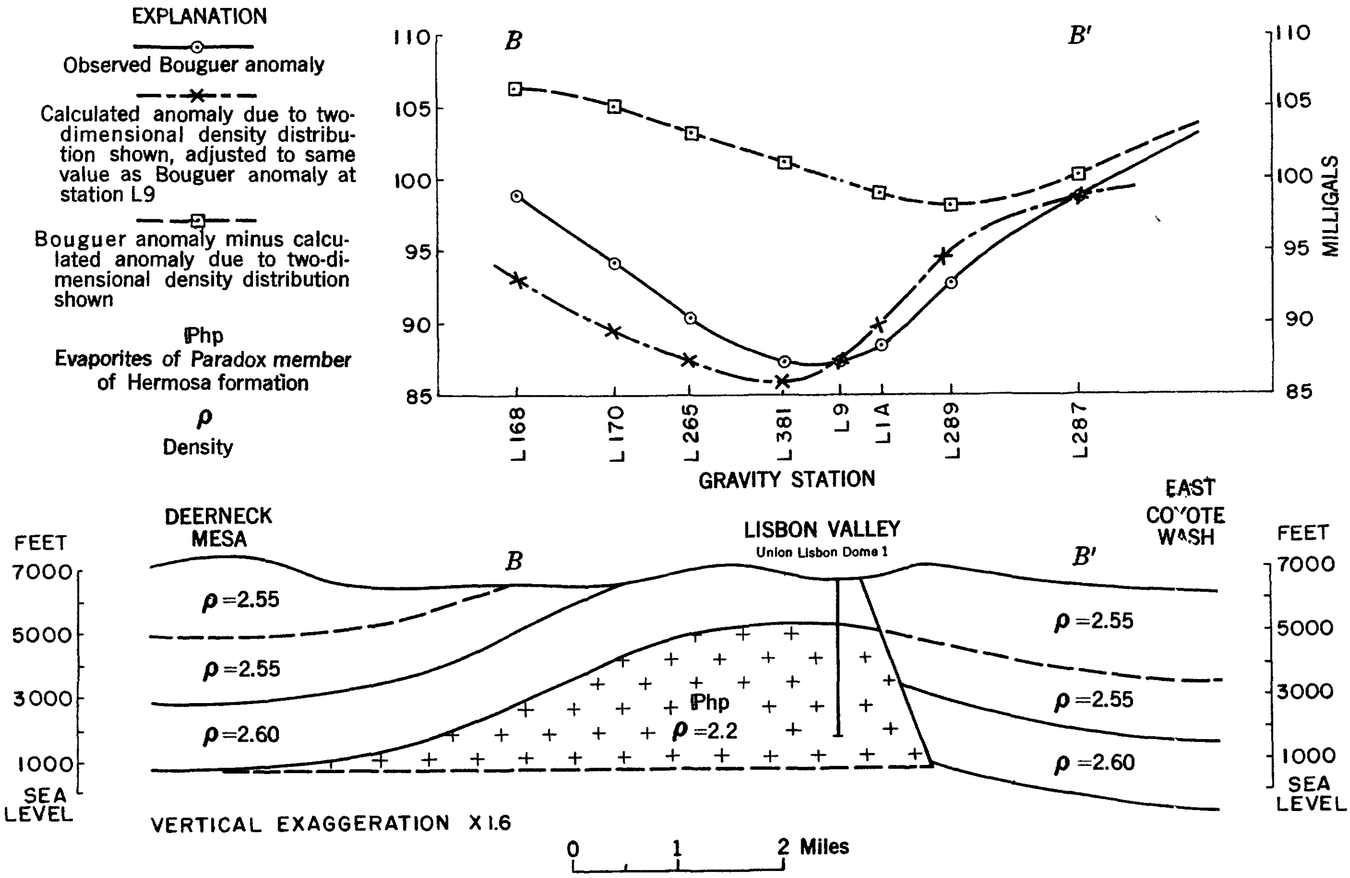


FIGURE 20.—A two-dimensional analysis of the Lisbon Valley gravity anomaly.

Lisbon Valley the axis of the gravity high passing through Island Mesa and crossing Coyote Wash trends at an angle of about 30° relative to the axis of the syncline. In the vicinity of Island Mesa the axis of the syncline cuts across this high. The high extends southward and passes into a nose along the south side of Diappointment Valley, Colo. (Joesting and Byerly, 1959, pl. 3). Over this distance it closely parallels the curving trend of Gypsum Valley (fig. 18) which suggests that the anomaly is related in part to late Paleozoic withdrawal of salt into the Gypsum Valley structure, with concurrent thickening of the Cutler formation.

SALT PLUG NORTH OF PINE RIDGE

The reversal of dip and possible minor faulting in the valley north of Pine Ridge are due to an underlying salt plug. The axis of the plug approximately underlies Utah Highway 46 (pl. 7). Figure 21 is a two-dimensional interpretation of the anomaly along profile *C–C′*. The assumption is made in this interpretation that the basement surface lies about 3,500 to 4,000 feet below sea level and that the top of the salt lies about the same distance above the basement. The anomaly is evidently not two dimensional. The anomaly at station LS36 (fig. 21) of a three-dimensional salt plug with the same cross section along profile *C–C′* and a length along its strike of about 5 miles, is about 1 milligal less than the anomaly for the two-dimensional body. The anomalies can be made the same by bringing the top of the salt about 600 feet closer to the surface for the three-dimensional calculation. In view of the uncertainties as to position of the body and density contrasts, more detailed calculations are not warranted. The magnitude of the anomaly suggests that the Cutler formation and probably the upper part of the Hermosa formation are thin or absent over the plug, and that, consequently, it is a piercement plug, probably initiated in Cutler time.

This plug lies on the trend of the Gypsum Valley piercement anticline, as does the South Mountain group of igneous intrusions in the La Sal Mountains to the northwest. The parallelism between the Gypsum Valley structure and a marked aeromagnetic anomaly, which flanks it to the southwest, (Joesting and Byerly, 1959, p. 10) provides good evidence for correlating the structure with basement faulting. It would seem that

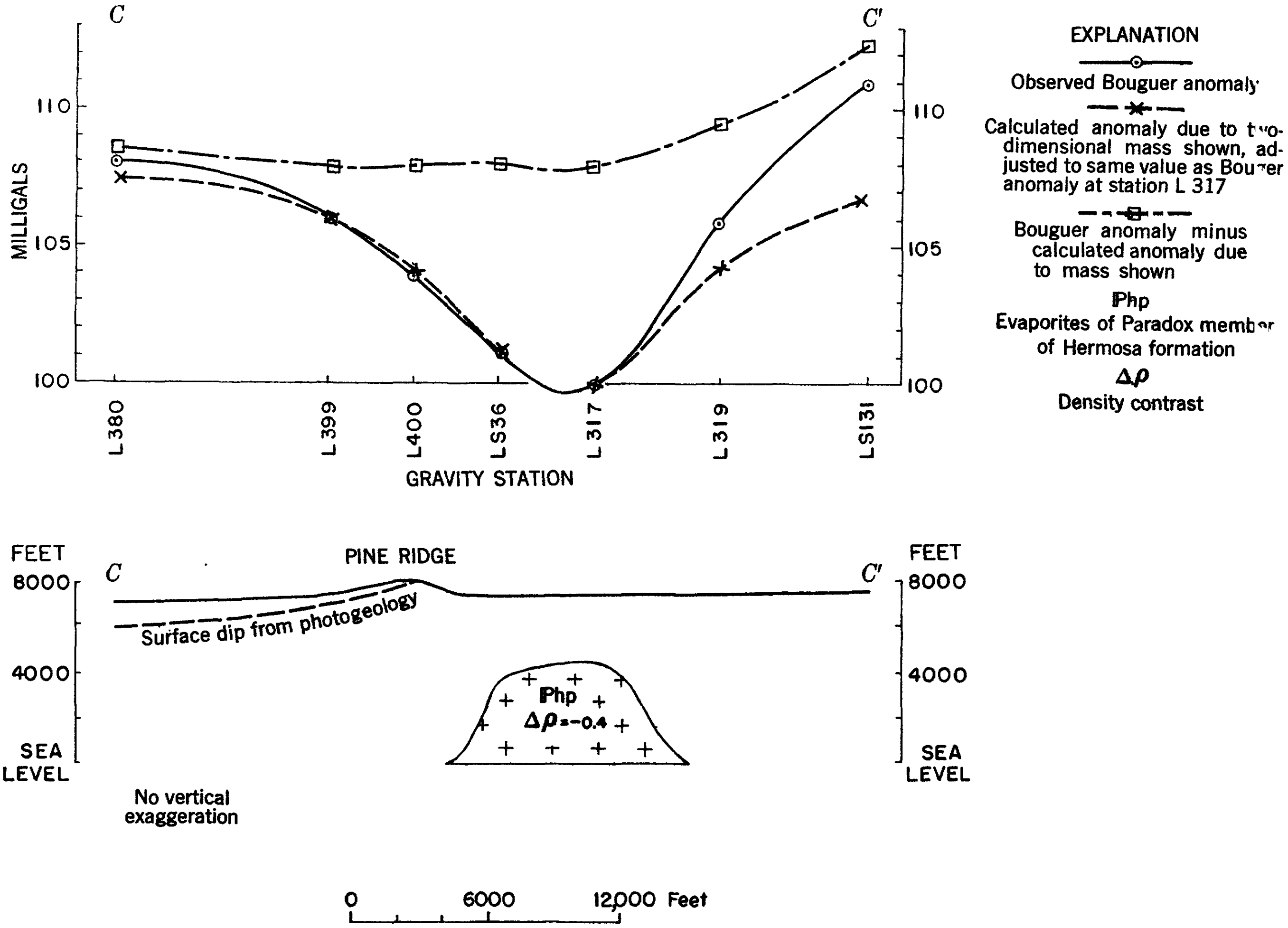


FIGURE 21.—A two-dimensional interpretation of the Pine Ridge gravity anomaly.

the location of the South Mountain group of igneous intrusions was determined by the old zone of weakness within the basement which was responsible for the initiation of the gypsum Valley piercement structure and the Pine Ridge salt plug in late Paleozoic time.

SUMMARY OF CONCLUSIONS

The magnetic anomalies and trends in the Lisbon Valley area are apparently caused predominantly by small to moderate variations of the magnetization of the basement rocks and to regional structural trends in the basement. In the eastern part of the area the magnetic trends are parallel to the northwest-trending structures in the sedimentary rocks, but in the remainder of the area they diverge westward from the major sedimentary structures.

Estimates of depths to the sources of anomalies indicate that the southwestern part of the area is apparently underlain by a basement ridge or platform bordered by a deeper basin to the northeast.

The gravity anomalies are due both to changes in thickness of the evaporites in the Paradox member of the Hermosa formation and to intrabasement density contrasts. Significant local thickening of salt and thinning or cutting out of clastic deposits in Cutler and Triassic time is indicated by the salt plug north of Pine Ridge and suggested by negative anomalies along the west flank and along the northwestward extension of the Lisbon Valley anticline.

The gravity anomalies complement the magnetic anomalies in the southwestern part of the area in indicating local east-west compositional trends within the basement rocks.

The alinement of the South Mountain group of igneous intrusions in the La Sal Mountains, the salt plug north of Pine Ridge, and the Gypsum Valley piercement structure, suggest that the South Mountain group of intrusions was injected along a zone of intrabasement structure, probably a fault zone, which originated before or during late Paleozoic time.

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