A STUDY OF REGIONAL GEOPHYSICAL DATA IN THE HOLBROOK AREA, ARIZONA

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An analysis of the available geophysical data in the Holbrook basin area of north central Arizona in Coconino, Navajo and Apache Counties has been made. This study has been supported by a contract with the Arizona Oil and Gas Conservation Commission, John Bannister, executive secretary, and the Four Corners Regional Commission.

The primary objectives of the analysis were to determine: (1) thicknesses and lithology of sedimentary column overlying Precambrian basement; (2) structural configuration of basement surface, faults in basement and sedimentary rocks; and (3) anomalous conditions within the sedimentary rocks potentially favorable for entrapment of hydrocarbons.

Location

The available geological data in the Holbrook area consists of reports from the Arizona Bureau of Mines, theses, and other publications from miscellaneous sources. Approximately 20 drill holes in the area (for which lithological logs are available) penetrate Precambrian basement. Formation density logs exist for a few holes adjacent to the area of interest and in one hole within the area (appendix A).

The Holbrook basin is located on the Colorado Plateau on a regionally northeast tilted homocline of Paleozoic, Mesozoic and minor Cenozoic sedimentary strata. Minor exposed igneous rocks are present in volcanic flows and small basic intrusions. Precambrian crystalline rocks are exposed only in the Grand Canyon, Defiance Plateau and beneath the Mogollon Rim. The "Rim" lies to the south, the Defiance Plateau to the northeast, and the San Francisco and White Mountain volcanic fields to the west and the southeast, respectively.

There are no published detailed geological studies of this particular area; most mapping has been of a reconnaissance nature. The primary sources of geological information for this report are the Arizona Bureau of Mines Bulletin 182 (Peirce, et al., 1970) and Bulletin 185 (Peirce and Scurlock, 1972). They incorporate the most up-to-date information from drill hole logs and geological studies in the area. Isopach maps referred to in this study are from the former report. Passmore (1969) restricted her analysis to the Permian strata. Pine (1968) discussed the stratigraphy of the lower Paleozoic in adjacent areas.

General Geology

The pre-Cretaceous Mogollon tilting and a Laramide deformation produced the general northeast dip now present in the Paleozoic and Mesozoic strata.

The Black Mesa basin to the north is a complex structural basin. The eastern limb is the Defiance uplift, the southern limb the Mogollon uplift and the western limb the Kaibab uplift.

"The 'Defiance' lends itself to a plateau, an uplift and a region of positive tendencies and sedimentational influences throughout much of Paleozoic and Mesozoic time.....as applied to paleogeographic phenomena, it can be rather loosely used to describe numerous stratigraphic patterns reflected on the surface and in the subsurface. In Arizona a positive tendency has been commonly envoked to explain the southeast and northerly wedge out of Cambrian, Devonian and Mississippian strata; the eastward, northward and northwestward wedge out of the Permian Kaibab Limestone..." (Peirce, et al., p. 46, 1970). This persistent "positive tendency" has been an area of geological activity up to the present as can be seen by the existence of the Defiance Plateau at the center and volcanic activity along its margins (figure 1).

Lower Paleozoic

Cambrian, Devonian and Mississippian strata present in the area range from zero to 500 feet of

basal siliceous clastics, dolomites and shale (figure 2). They are thought to have been deposited mainly in the northwest-trending Mogollon Sag of Huddle and Dobrovolny (1952) and the northeasterly-trending Oraibi trough of Turner (1958), the latter feature lying between the Kaibab and Defiance uplifts. Thicker to the west, they pinch out onto the Defiance uplift to the east. The Cambrian isopach map, based on a few points, indicates that a positive enclosed the northern portion of the Holbrook area and perhaps extended as far west as Mormon Lake (Peirce et al., 1970, plate 11A). This positive persisted through the Devono-Mississippian although extending considerably less westward. The distribution of these Lower Paleozoic rocks is probably due to pre-Pennsylvanian Naco erosion, as well as local embayments and promontories during sedimentation. An example may be the narrow positive feature appearing on the isopach maps extending westward from the Defiance positive. Renewed activity in the Holbrook area throughout the Paleozoic is indicated by the stripping of the Mississippian strata from even minor structural highs.

These basal Paleozoic rocks could serve as reservoir rocks when juxtaposed with overlying marine source rocks. Basal fetid dolomites near Payson have oil staining.

Upper Paleozoic

The Pennsylvanian Naco Formation uncomformably overlies Precambrian to Mississippian rocks. More than 700 feet of these siliceous clastics and carbonates have been deposited in the northernmost portion of the "Pedregosa embayment" (figure 3). The formation thins and changes facies and becomes a shale to the west. It pinches out to the northeast and east on the Defiance uplift and is thickest in the Holbrook area.

There was continuous deposition of up to 700 feet of Permian Supai red bed clastics, sulfates, and carbonates. After the deposition of the Fort Apache Member of the Supai, subsidence formed the Holbrook evaporite basin. Up to 1300 feet of anhydrite and halite mixed with carbonates and shales were deposited, often along "narrow zones with steep edges." The Supai is thickest in the Holbrook area, thinning in all directions. Some of the Fort Apache itself is a fetid dolomite with oil staining. Because of this, much exploration has been directed toward it. After subsidence and basin filling ended, the evaporite history was terminated with a wide-spread blanket-like deposition of anhydrite.

Deposition of the Permian Coconino Formation followed. This light colored clean quartzose sandstone ranges from 800 feet of eolian sand at Flagstaff to 200 feet of waterlain sand in New Mexico. Although this porous sandstone is primarily a source of helium it may provide a reservoir for oil as the Kaibab overlays it. Some oil shows have been noted.

The whole Holbrook area has been tilted to the northeast by the pre-Cretaceous Mogollon uplift. The Laramide pulse of the Defiance uplift has also impressed itself upon the area although the major component of the present structural tilt is pre-Upper Cretaceous in origin.

GEOPHYSICAL DATA

The recently completed Regional Bouguer Gravity of Arizona by R.E. West and J.S. Sumner (1972) consists of stations distributed at a minimum of five-mile intervals throughout most of the state, with a more dense distribution in some areas (Bouguer Gravity Anomaly Map of Holbrook Area, Arizona). Although topographic corrections were not made, the relatively low relief has negligible terrain effects. There has been little interpretation of the data on the Colorado Plateau thus far (West, 1972).

The Aeromagnetic Map of Arizona (W.A. Sauck and J.S. Sumner, 1970) consists of north-south lines flown at constant barometric altitudes of either 9000 or 11000 feet at three mile intervals over the state. Readings along the lines can be considered to be almost continuous (Residual Aeromagnetic Map of Holbrook Area, Arizona). There has also been little interpretation of this data in the Holbrook area

(Sauck, 1972).

Gravity would provide the most direct method of determining thicknesses and lithology of the sedimentary column (objective No. 1), providing that accurate residual gravity values can be determined.

The information available in magnetic data is very likely to be dominated by the more magnetic phases of the basement rocks, the overlying sedimentary strata having a negligible effect on the magnetic field.

Determining the structure of the basement (objective No. 2), can potentially be achieved with both methods. Possible structures in the sedimentary strata are difficult to interpret unless significant density changes occur in the strata or the structure is a reflection of topographic features on the basement surface.

The analysis of the gravity data has been the primary source of the structural interpretation in the Holbrook basin.

Both gravity and magnetics are potential fields, therefore, solutions are ambiguous. Magnetics, however, provides a complementary technique to gravity which can aid in resolving these ambiguities since the two methods respond to different rock parameters, magnetization and density, respectively.

Stratigraphic logs for the drill holes in the area were matched with density values from density logs and other sources, for their corresponding rock types (a listing of the interpreted compensated density log data and their corresponding lithologies are included in the appendix). The Arizona Bureau of Mines bulletins have utilized these drill holes for building stratigraphic sections. Their analysis was a valuable aid to our interpretation (Peirce, et al., 1970, and Peirce and Scurlock, 1972).

West (1972) concluded that a density contrast of -0.20 g/cc was an adequate generalization for the difference between Precambrian basement and the Paleozoic and Mesozoic sedimentary formations. After analyzing the formation densities and other workers' values (Plouff, 1967), this report concludes that for the Holbrook area the contrast is between -0.16 to -0.25 g/cc with an average of -0.20 g/cc. The greatest density contrast in the sedimentary column is the facies change from sulfates and carbonates to principally halite in the upper Supai.

An accurate residual gravity is necessary for interpretation. The "residual gravity" desired in this modeling are those gravity anomalies which are due to changes in the character (thickness and lithology) of the sediment overlying the basement, lateral mass changes in the basement being excluded. In the case of a local study, a single basin between mountain ranges or some other local feature a few miles or tens of miles in geographical extent is being analyzed. The assumption of lateral density homogeneity can be reasonable in such cases. However, the Holbrook area is approximately 100 x 60 miles. Accurate analysis requires that data beyond the area of interest be considered also. There is little justification for assuming a lateral homogeneity in the basement over large distances.

When comparing gravity and magnetic anomalies the relative resolution of the two surveys must be taken into consideration. The gravity survey usually has a minimum five-mile separation between stations in the Holbrook area. The magnetic survey has almost continuous readings along north-south trending flight lines spaced at three mile intervals. By considering the well known formulas for computing the depth to buried ridges (horizontal cylinders) from the wavelength of the anomaly, it is seen that both these geophysical surveys have similar degrees of resolution.

The gravity anomalies in this study have been analyzed assuming either: (1) a one layer constant bulk density contrast between the sedimentary strata and the basement rocks, or (2) a vertically and laterally variable density contrast. These two approaches were used concurrently. The results of the constant density contrast method were subsequently analyzed by applying reasonable variable density values to determine the conditions which would be necessary to remove basement features indicated by modeling with a constant density contrast.

Because of the ambiguity of potential fields, a broad basement uplift will produce a broad wavelength gravity anomaly as will a much narrower horizontal cylinder buried considerably deeper than

the basement uplift. The automatic curve matching gravity program used in this study fits layered vertical prisms to the residual gravity anomaly. The two solutions converge only when gravity stations are closely spaced and a narrow vertical prism converges to a horizontal cylinder in two dimensions. An example is Station 6.5 on Line 1 (figure 6). A ridge with its top at 4000 feet has been interpreted. If the anomaly is analyzed with the half wavelength formulas the depth to center is 1000-2000 feet, roughly corresponding to the vertical prism solution.

Since the main concern is the character (density, thickness) of the sediments overlying the basement, the separation of the residual anomalies from the regional anomaly can be estimated from drill hole data. If a gravity anomaly at a point is only due to less dense sedimentary strata overlying the basement the regional gravity value can be estimated if the depth to basement is known. This is done by adding to the Bouguer gravity value the gravity effect of that sedimentary strata, using the Bouguer slab and the appropriate density contrast. The regional gravity subtracted from the Bouguer gravity anomaly is the residual gravity. If Precambrian rocks outcrop in the area the regional gravity is the same as the observed gravity. The residual is then zero. Since no such outcrops occur inside or adjacent to the Holbrook basin, only drill hole data was utilized. Initially it is assumed that the basement density between holes can be interpolated. Concurrent magnetic interpretation may aid in resolving some gravity interpretations. If it can be shown that the feature causing a magnetic high is situated over a gravity anomaly, there is a question as to whether this susceptibility high accompanies a lateral density change. If the gravity and the magnetic models both indicate a similar basement feature, it is reasonable to assume the feature does exist.

As noted previously, in this report the interpretation will be primarily based on the gravity data. Magnetics will be used as an aid when questionable interpretations are involved.

Interpretation of Geophysical Data

A cursory comparison of the elevations of the basement to the relative gravity highs and lows on the Bouguer Gravity Map of the Holbrook Area would at first seem to have a close correlation, basement elevations as well as gravity decreasing west to east and south to north. Only when basement elevations and gravity to the north of Holbrook, northeast toward the Defiance Plateau and east to New Mexico are considered is there an obvious anomalous inverse correlation. The residual gravity of interest in this report is considerably different than the Bouguer gravity map.

The Holbrook basin lies in a prominent low of generally subdued gravity anomalies. It is at the southwestern end of a strong northeast-striking gravity gradient that trends for at least 120 miles toward the Four Corners area. Gravity values to the east of this structure are characterized by values of 215 milligals or lower, while to the west, with local exceptions, values are generally about -180 milligals or higher. The 35-milligal decrease in a 10-mile or less interval is too steep a gradient to be explained by a simple change in the depth to the basement. East of this gradient lies the Defiance Plateau with outcrops of Precambrian rocks. As the regional gravity decreases the thickness of the overlying sediments decreases, the inverse of the normal relationship if the regional gravity was directly due to changes in thickness of the sedimentary rocks over the basement. There must be a significant change in the density regionally of the basement rocks across this trend. A general fault-type structure could occur at a depth of approximately 10,000 to 15,000 feet below the surface (3000 to 5000 feet below sea level). Another possibility is that the density change could be distributed over a large interval in the crust. A corresponding narrow magnetic lineation on the magnetic map parallels this gravity feature and is one of the most outstanding magnetic anomaly trends in the state (Northeast Lineation). This anomaly is due to the edge effect of a slope dipping to the east. The Defiance uplift to the east was an intermittent positive during the Paleozoic and Mesozoic (Peirce et al., p. 46, 1970). A Precambrian outcrop at 7000 feet elevation near Ft. Defiance is the highest elevation of Precambrian in that part of the Arizona

Colorado Plateau. West of the gradient in the Black Mesa area the basement is below sea level. The gravity and magnetics indicate a shallower depth to a top of a structure in the area west of the Defiance positive than to the east. The drill holes penetrate metamorphics and granitics to the east as well as the west. Probably too few drill holes penetrate the basement to accurately correlate basement rock type with regional gravity and aeromagnetics. The structure of the rock causing this prominent trend may lie at a greater depth than the top of the basement. Perhaps the numerous Tertiary vents and intrusions of the type found in the Hopi Buttes area north of this trend are related to this structure, and possibly are genetically related to the structure that does cause it.

Isopachs of the Paleozoic strata (figure 1) show a persistent Defiance positive extending westward through Holbrook. The general positive tendency in the Lower Paleozoic appears to outline the regional gravity, although inversely; lower gravity values relating to structural positives. The striking coincidence of this positive tendency and the general gravity low would seem to be related. The regional gravity reflects intra-basement structures and petrology which could have had their origins even in the Precambrian. An indication of recent activity along the Defiance positive can be the existence of the Defiance Plateau and the distribution of Cenozoic volcanics along its margins.

If the Free Air gravity is considered, the areas of the Defiance positive and the eastern portion of the Holbrook area have negative values, whereas the rest of the Colorado Plateau has Free Air gravity values which oscillate about zero. From this it can be concluded that the Defiance uplift has a mass deficiency, in an absolute sense, underlying it. The gravity is not due to a mass excess west of it.

Generally speaking widespread areas of negative Free Air gravity could be considered to be out of isostatic equilibrium. However, the short wavelength (at least on the Arizona side) of the Defiance gravity low and the thick nature of the underlying crust and lithosphere over the plateau leads to the conclusion that it is not necessarily the site of presently active tectonism related directly to that disequilibrium. The mass deficiency may be reflecting a feature "frozen" in the earth's crust and whose origin is in the Precambrian.

Although this feature apparently only exists in the northernmost edge of the Holbrook basin it must be taken into account due to its possible effect on the magnetic and gravity anomalies at Holbrook. If this structural feature underlies the Holbrook basin it will produce regional gravity anomalies which must be separated from the Bouguer gravity. Two magnetic anomalies have been modeled along the strike of the Northeast Lineation in an attempt to trace its possible extension through the Holbrook area. Both the Holbrook Magnetic Anomaly (figure 5) and Magnetic Anomaly No. 2 (figure 4) indicate a sloping basement structure with a slope to the east. The lineation appears to bisect the Holbrook area.

Steep gravity gradients of similar amplitude and slope surround the basin on the north and west edges. A relatively narrow east-west trending gravity high forms the southern border of the area. The San Francisco volcanic fields occur on the west edge of the Holbrook low and the White Mountain volcanic fields to the southeast. Basic Tertiary intrusives occur along the northern side of this gradient at Sunset Mountain southwest of Winslow. An elongate gravity high appears to connect these Tertiary intrusives with those at Elephant and Castle Buttes near the Hopi Buttes north of Holbrook (figure 6). Both intrusive locations are sites of local residual gravity highs expressing the intrusions of these dense rocks into the less dense Paleozoic and Mesozoic sedimentary strata. These areas lie along two model profiles, lines 2 (figures 7B and 11) and 1 (figures 6 and 7A) respectively, which will be discussed later.

Analysis of the Gravity Lines

Five lines were picked for gravity modeling based on (1) the location of drill holes in order to determine the residual gravity, and (2) maximum analysis of the salient features of the Holbrook area. Magnetic models were constructed for anomalies coincident with gravity anomalies to lessen the ambiguity in gravity interpretation. The lines sometimes extend, as in the case of Lines 1, 2 and 3,

beyond the area of interest. This was necessary for regional control though detailed modeling was not always carried out very far beyond the area of interest.

The initial model profile was Line 1, trending northerly from the vicinity of Show Low (DH 368) to Holbrook and thence to a point on the Hopi Reservation (DH 307), a distance of 120 miles. All drill hole numbers correspond to Arizona Bureau of Mines numbers or those of the Oil and Gas Conservation Commission permit numbers, the latter for the more recently drilled holes. They are listed in the ABM Bulletins 182 and 185. DH 312 to the north was used for regional control. Seven drill holes occur near this line so that relatively tight control existed for the regional gravity. In addition, good approximations of the density values of the rock types in the central portion of the profile could be made.

Line 2 trends southeasterly from near Winoma through the center of the Holbrook basin to just east of Show Low, along six drill holes, a distance of 90 miles.

Line 3 trends easterly for 120 mlles from near Turkey Mountain in the San Francisco volcanic field through the center of the Holbrook basin to just north of St. Johns. Seven drill holes were used for control.

Line 4 is a branch of Line 3, starting at DH 71 on Line 3, near Chevelon Butte, to DH 291, south of Holbrook, to DH 8 northeast of Holbrook, a total of 60 miles. This line was modeled to avoid the adjacent steep regional gravity gradients on the north and south and to model more of the central basin.

Line 5 trends northeasterly from DH 39 in the center of the basin to DH 57, 30 miles east of Holbrook, a distance of 40 miles. This line bisects a broad gravity high which predominates the eastern part of the area of interest.

Each of these lines and accompanying magnetic anomaly modeling will be discussed in detail in the section which follows.

The five cross-sections consist of the residual gravity profile, the computed gravity profile, topographic profile, basement profile, drill hole data and interpreted geology. The points on the cross-section are gravity stations which were used for analysis by West's (1972) iterative curve matching computer program. The gravity anomaly which was used for analysis is the residual gravity and the matched model produces the computed gravity profile. Drill holes along the profile are indicated and are used for regional gravity and stratigraphic control. Mapped structural, topographic and geographic features are also noted.

The stratigraphy has been interpreted between drill holes incorporating the results of the gravity modeling. The formations are:

SYMBOL	AGE	FORMATION	GENERAL LITHOLOGY
Qa	Quaternary	"Puerco River"	alluvium, river deposits
Ti	Tertiary	Hopi Buttes, others	basic intrusives
Pk	Permian	Kaibab	limestone, shales
Pc	Permian	Coconino	porous quartz sandstone
Psu	Permian	Upper Supai	shales, sandstone, dolomites, limestones, and evaporites (including halite)
Pft	Permian	Fort Apache	gray limestone
Psl	Permian	Lower Supai	same as Psu except less halite
Pn	Pennsylvanian	Naco	limestone, shales
Mrw	Mississippian	Redwall	cherty limestones
Dm	Devonian	Martin	dolomites, shale
C	Cambrian (?)	unnamed	clastics

Formations above the Kaibab are not discussed or shown since they are not significant in the area of interest.

Line 1

There are seven drill holes located on this line, providing more detailed control than any other line (figures 6 and 7A). It begins at DH 368 at the southern edge of the Holbrook basin and extends to DH 307 in the Black Mesa area to the north.

The general surface geology and subsurface geology as seen in drill holes along this line is essentially the northward dip related to the pre-upper Cretaceous uplift. Oil shows have been noted in the Permian Supai Formation, especially in the vicinity of the Fort Apache Member. Further to the north the oil shows were in the Devonian Elbert and Aneth Formations. Many of the drill holes have used anticlines as targets, for instance, the so-called "Holbrook Anticline".

The Holbrook gravity low can be seen on the regional gravity to be in general due to a density change of a larger deep basement structure. The line is approximately coincidental to Peirce, et al's (1970) Plate No. 8 cross-section.

Two models were used. A constant -0.20 density contrast and a laterally variable density contrast (-0.16 to -0.24) reflecting the lithology logs on drill holes in the area. The two solutions had very close correspondence.

Significant basement highs are indicated at Stations 4, 6.5, 15 and 21. At Stations 4 and 6.5 the line crosses gravity highs indicated by single gravity stations although subsequent gravity readings in the vicinity of the anomaly corroborated their existence. These are just south of the so-called "Holbrook Anticline" and at the east end of a general gravity high which is at least partially due to a density increase related to Quaternary volcanism. This can be seen by the short wavelength circular gravity and magnetic anomalies, such as Magnetic Anomaly No. 3 (figure 8) in this area of Quaternary sediments and volcanics north and northwest of Show Low. The gravity and magnetic anomalies here correspond very closely. These anomalies in turn lie on a more regional west-trending gravity high extending from St. Johns near DH 7 to the San Francisco volcanic fields on the west. Only two drill holes on this trend penetrate basement, DH 76 and DH 370. Both holes bottomed in "metamorphics", possibly greenstones. If a basement high does exist at Station 4, it could be caused by the adjacent density change. A Lower Paleozoic ridge is indicated in the isopach maps (figure 2). The regional gravity may be in error.

The two adjacent apparent basement highs at 15 and 21 may be related. The high between Stations 21 and 24 is in the vicinity of the Hopi Buttes Tertiary plugs which appear at the surface at localities such as Castle and Elephant Buttes. A general gravity high more or less parallels that regional gravity low. The west end of this high is traversed by the gravity line 2 (figures 7A and 11) and is also in the vicinity of local Tertiary intrusives. The gravity high at 21-24 could be due to the intrusion of basic Tertiary intrusives into the basement and sedimentary rocks. A basement high and lateral density change from granite to denser greenstones could also exist at the same time.

There is a significant gravity high at Station 15. This almost circular gravity high is present northwest of Holbrook in the general vicinity of the most prominent magnetic anomaly in the area, the Holbrook Magnetic Anomaly (figure 5), and is somewhat obscured by the regional gradient. The residual anomaly is a feature 16-20 miles in width (figure 9). Its proximity to the Holbrook magnetic high necessitated the modeling of the latter to determine any correlation between the magnetic anomaly and the gravity anomaly. The cause of the magnetic anomaly is 12 miles in width and only overlaps the gravity anomaly partially. The elevations of the cause of the magnetic anomaly was 1500', the same as the adjacent depth to basement. Line 1 only crossed one corner of the gravity anomaly, the actual maximum being -185 milligals.

A magnetic model was computed of the basement topography determined by the gravity modeling

(figure 10). The purpose was to determine if only the relief of the metamorphic and granitic basement with a constant lateral susceptibility could cause the magnetic anomalies in the area. According to Marsh (1971) and Sauck (1972) topographic features five or six thousand feet above background will not produce the anomalies of several hundred gammas such as those found in this area when observed from 9000 foot elevations regardless of the line spacing. This is also true for basement relief, the overlying sedimentary sequence having a negligible effect. The magnetic expression of the basement with a susceptibility greater than that of the Holbrook Magnetic Anomaly cannot alone explain the observed magnetic anomalies.

The gravity high may be due to a basement topographic feature partially, but is most certainly a density change also. It may be another extension of the Tertiary intrusions seen further north. If the gravity anomaly is exclusively due to a basement density increase, the center of a horizontal cylinder is at 10,000 feet below sea level. Neither solution coincides with the magnetic solution. The northern edge of this anomaly is not exactly defined due to lack of data and the contours are interpretive. The Black Knob Anticline trends into the area of this anomaly and may indicate some structural relief is involved. Most of the anticlinal and synclinal features mapped in the Holbrook area are subtle features. Closures related to these features would likely be slight.

Conclusions Line 1

The possible basement highs at Stations 4 and 15 could be reflected in the sedimentary strata although there is no surface indication of such a structure at Station 4. The apparent coincidence of the Devonian high between DH 368 and DH 961 and the Defiance high in the Paleozoic in the area of Stations 15-25 may indicate the lateral density change in an intrabasement feature. However, the Black Knob Anticline at Station 15 may indicate that more than just a lateral density change exists. There are no drill holes in the area. More stations along the entire line would provide a much more detailed look at the structure. Gravity stations should at least be established at more drill holes which penetrate the basement for a more accurate regional gravity. With six drill holes at a relatively close interval, tight control is available for a detailed analysis. Structural lows indicated between Stations 4 and 8 could provide a suitable environment favorable for oil accumulation. The isopachs indicate a more widespread distribution of Lower Paleozoics west of the Defiance Positive (figure 2).

The lithology has a sharp lateral change in this area throughout the sedimentary column; red bed clastics, carbonates and sulfates laterally change into halite in the Upper Supai and carbonates into shales, in the Naco. The location of the hingeline of the evaporite basin does appear to be very near to DH 291.

Line 2

Seven drill holes are located along this line (figure 7B and 11). Since the structure is dipping to the north and northeast this line is approximately parallel to the regional structural strike.

The regional gravity was difficult to determine at the northwest end of this line. The northeast-trending gravity high mentioned in Line 1 is in the area of basic Tertiary intrusive outcrops at Sunset Mountain. A 20-milligal closed gravity low west of these intrusives could be due to the gravity effect of the basic intrusion, masking and separating the gravity expression of the sub-basement structure to the east from its continuation in the west. The stratigraphy correlates across the gravity high with a flat dip from DH 186 to DH 961. Structurally low areas are indicated east and west of the DH 961-39 area. The subtle high indicated at DH 961 on line 1 is also seen on this line. There is a magnetic high near DH 961 which was modeled as Magnetic Anomaly No. 1 (figure 12). This model indicated a vertical prism source with the top at an elevation of 2000 feet. The model, therefore, did not resolve whether the cause of the gravity and magnetic anomalies near DH 961 was the same body.

The general basement relief between DH 961 and DH 20 is low until the effect of the Tertiary intrusives west of DH 20 is approached. A broad basement low is also between DH 39 and DH 76-370, the last drill hole being in the White Mountain volcanics near the Mogollon Rim. However, this low is removed if the model assumes that the Coconino and Upper Supai formations have a constant thickness between DH 39 and DH 370, but an abrupt change in density in the Upper Supai. This formation is assumed to change from more dense sulfates and carbonates (-0.20g/cc) to less dense halite (-0.50g/cc) from south to north. This can account for the residual gravity anomaly. Another possible facies change is from halite to clastics north of DH 20. A low is indicated just south of this proposed facies change. It is also removed by applying the assumption of an introduction of a predominantly halite Upper Supai. The relationship of the Pennsylvanian rocks to the adjacent formations and the isopachs does, however, indicate they may actually be thicker southwest of DH 961.

Conclusions Line 2

The structural relief along most of this line which is along the sedimentary strike is very subtle. Only the lowermost Pennsylvanian Naco and the Devono-Mississippian formations would seem favorable for basin oil entrapment with regards to structural traps. However, the oil Shows to the south were in the Upper Paleozoic Supai and Coconino formations. The halite/clastic and halite/carbonates and sulfates facies changes could be the site of more subtle traps.

More gravity stations around Magnetic Anomaly No. 1 would determine whether an isolated gravity high exists and whether it has the same cause as the magnetic anomaly. This line crosses a west-trending Lower Paleozoic ridge extending west from the Defiance uplift and along the southern flank of an Upper Paleozoic ridge. Although some thinning of the Paleozoic strata is indicated, this more probably indicates a density change related to the processes that caused the uplift.

Line 3

This profile is an east-west line with seven drill holes along it (figures 13 and 14). The high indicated at Station 3.8 at Turkey Mountain correlates with Magnetic Anomaly No. 4 (Bouguer Gravity Map of Holbrook area). The high amplitude indicates basic igneous rocks.

The east-west elliptical gravity high west of Show Low (discussed previously) increases to a maximum of -190 milligals while the regional values on both sides are lower. It lies between DH 71 and DH 291 along this line. The Paleozoic isopach maps indicate a gradual thickening of the Paleozoic from DH 71 to DH 291, as well as the introduction of the halite section. A steep regional gravity gradient increasing to the south and intersecting Line 3 at Station 12 was determined from a northeast-southwest gravity profile which included DH 85 and DH 291. The regional gravity at Line 3 in this area was therefore estimated. All the Bouguer gravity is not accounted for by this regional. A basement high remains at Station 12 and is in the area of a structure which has been mapped as the Richard Lake Anticline by reconnaissance mapping. There is a broad low between DH 39 and DH 6, but little detail due to few gravity stations.

Magnetic Anomaly No. 2 (figure 4) which occurs between Stations 7 and 12, was modeled and discussed previously as being an extension of a regional northeast trend. This anomaly strikes north-northeast to north. Faults striking north are indicated in this region by the Arizona State geology map and Peirce, et al., (1970), plate 1, upthrown to the northwest. More detail gravity surveying would be necessary to determine if there is a correlation between the gravity and magnetic anomalies and the surface structure.

Magnetic Anomaly No. 3 lies south of this line. A reasonable model of the source is a vertical prism with the top at the 2000 foot elevation (figure 8). The modeling fits the interpretation that this area

is one of Quaternary basalt intrusions.

Conclusions Line 3

Possible basement highs are indicated by the gravity at Stations 7, 12 and 16 and correlate roughly with surface mapped "anticlines", the latter two being the Richard Lake and Holbrook "Anticlines". An extension of the Richard Lake Anticline is not mapped this far south (see Line 4) on the surface and the possible extension of this feature should be considered.

There are few stations east of DH 39. A broad low is indicated, but the line parallels a relatively narrow Bouguer gravity low. The isopachs of the Paleozoic show a thickening here of the upper Paleozoics (figure 3). Additional stations both at and between DH 71 and DH 6 would be helpful for detecting a more detailed structure.

The halite section in the Upper Supai is not seen at DH 71 but appears at DH 291. If a variable density model is used with the facies change just east of DH 71 the steep basement low between Stations 7.2 and 11 is removed, while the high at 12 and the low east of 12 remain. The assumption of a halite facies extending almost to DH 71, therefore, seems to be supported by the modeling.

The region of the basement low between DH 39 and DH 98 was also reanalyzed. A strong facies change is not indicated in the Upper Supai from the drill hole logs. An increase in the thickness of the halite section or a considerable decrease in the density of the Naco could explain the 2 to 4- milligal change. The latter possibility would require an unreasonable increase in the density contrast, from -0.10 to -0.40g/cc. Isopachs of the Upper Supai (Peirce et al., 1970, figure 11) indicate a thicker section between DH 39 and DH 98. A 400-foot increase in the thickness of the halite could cause a 3 milligal anomaly.

Line 4

This line somewhat parallels Line 3 and was meant to further analyze the central Holbrook basin (figure 15A and 16). Because of the difficulty in determining the regional along Line 3, Line 4 follows a profile which has more drill holes for regional control through the area of the Richard Lake Anticline. This is provided by DH Union-Continental 1-A which bottomed in Martin shale, possibly very close to the Precambrian. Since a gravity high extends northward the regional gravity at DH 20 on Line 2 was also used for Line 4.

Basement topography appears to follow mapped surface structures, a syncline and anticline. This may be an extension of the Richard Lake Anticline, which is also seen at Station 12 on Line 3. If the same variable density parameters as those on Line 3 are applied here, the low at Station 2 is removed, but the high to the east remains.

The high at Station 12.2 on Line 4 should be field checked. A sharp low at the Puerco River is at least 3 milligals lower than background. This anomaly is probably due to a section of recent river sediments in the Puerco River Valley. The Puerco River is prominently expressed by a large anomaly due to the low density of recent river deposits, the close proximity of this low density section to the observer and the wide station spacing. If closely spaced stations were observed in a traverse across the valley the effect of the river sediments could be readily subtracted. A layered model which included a 500 foot section of -0.50g/cc river deposits can account for the gravity low and not require a basement low.

Conclusions Line 4

Oil shows occur near the Ft. Apache member of the Supai Formation at DH 71 and 85 and also

in the Naco and Martin in DH U-C (1-A).

A strong structure, if related to the Richard Lake Anticline, extends much further south in the subsurface than originally mapped. This structure should be re-examined. Establishment of more stations between DH 71 and DH 85 would be desirable for a more accurate delineation of the basement topography.

Line 5

The regional gravity (figure 15B) was determined from drill holes outside of a broad Bouguer gravity high which lies in the east-central portion of this study. The aeromagnetic map indicates a broad magnetic low. The drill holes inside this area did not penetrate the Precambrian. The resultant model determined from the gravity has two basement highs (figure 17). Both coincided approximately with anticlines mapped on the surface. These anticlines have been targets of several shallow drill holes. The deepest hole was drilled to 2665 feet elevation near Station 6.6, bottoming in Lower Supai. The modeling indicates an extremely thin section of sedimentary strata. According to the model the sedimentary section would have to be as thin as 1500 feet in the west and 2000 feet in the east. This would require a thinning of the Lower Supai and Naco formations over the apparent basement highs. The drill holes in the area are all too shallow to determine the extent of the disagreement between the modeling and the actual geology.

If the regional gravity was a constant gradient with a higher absolute gravity value thicker strata would result over the highs. It would also result in an even thicker section at Station 6.6. The thicker Paleozoic present to the south could trend more north-south and support the contention that a basement at Station 6.6 is apparently deeper.

A model with a lower density contrast due to denser sedimentary strata would result in a thicker sedimentary column. This seems unreasonable in light of the apparent greater thickness of the halite in this area.

Conclusions Line 5

The relative structure indicated by the gravity model agrees well with the surface geology. The actual depths of the basement are probably deeper than that indicated and the regional gravity more complex than a constant gradient. A broad regional gravity high would seem to be more reasonable if the Bouguer gravity was fitted to a trend surface. The low between Stations 7 and 8 would remain.

Since the highs are apparently related to mapped "anticlines", basement uplifts are indicated. A situation similar to that on Lines 3 and 4 most probably exists. There is a density increase as well as a basement high. Perhaps there is a genetic relation between the basic Tertiary intrusive occurring less than 10 miles to the north and the gravity high as is perhaps the case in Lines 1 and 2.

More stations are desirable all along the line. It would also be helpful to determine how the Tertiary intrusives immediately to the north are related to the gravity. It would aid in redefining the regional gravity along Line 5.

GENERAL CONCLUSIONS

The gravity and aeromagnetic maps of the area strongly reflect intrabasement structures. Drill hole information has aided in analyzing the regional gravity with respect to the residual gravity. The residual gravity along the five gravity lines display more apparent structure than the surface geology. Interpreted basement highs and lows are new areas of interest in a traditional structural analysis. Alternate solutions for this basement topography are abrupt, drastic density variations in the sedimentary

column. Subtle types of oil traps could occur at these sharp lithologic variations.

Considering the possible environment and fracturing provided by the intrusion of basic igneous rocks, these areas should not be discounted as favorable for oil accumulation. Most of the oil production in Arizona is related to the edges of a consistently active geological structure, the Defiance uplift, which has recent Cenozoic volcanics at its periphery. Most of the state's oil production is from an igneous sill reservoir along the edge of the Defiance uplift. The modeling of the residual gravity has indicated local structures which could be related to igneous activity. The regional gravity displays the intrabasement structure outlining the Defiance uplift.

This has been a regional analysis. Subtle, local anomalies cannot be sufficiently analyzed unless closer station spacing is provided. The data discussed herein provides an excellent framework from which more detailed geophysical surveys of all types may be launched. Gravity stations should be established at all drill hole sites and localities of Tertiary intrusives for a more accurate control on regional gravity. Sufficient drill hole data exists for the central basin so that detailed lines could then be surveyed connecting these drill holes with even closer station spacing. Topographic sheets at 7.5' scale are now available covering the Holbrook basin. More detailed analyses may then be possible of such features as the extent and thickness of the salt.

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APPENDIX

Formation Density Logs

OGC #371

Tenneco Merrill #1; T. 10 N., R. 30 E., sec 26; elev. = 6968; lithology log #2064

Formation	Depth to bottom	Lithology	Density
Moencopi	183	sandstone (ss), shale (sh)	2.5
Kaibab	518	sh, limestone (ls)	2.65
Coconino	754	sh, ss	2.35-2.45
Supai	850	evaporites (evap), ss, sh, dolomite (dolo)	2.35
	1200	anhydrite (anhyd), ss, siltstone (slst)	2.5
	1444	evap, slst, ss	2.30-2.40
Fort Apache		ls, evap, dolo, slst	2.5

OGC #375

Tenneco Oil Federal "C" #1; T. 11 N., R. 28 E., sec 22; elev. = 6064; lithology log #2073

Formation	Depth to bottom	Lithology	Density
Moencopi	150	ss, slst	2.55
Kaibab	511	ls, sh	2.55
Coconino	800	ss, slst	2.30-2.35
Supai	1220	ss, evap, slst, dolo	2.30-2.40
Fort Apache	1450	slst, gypsum (gyp), dolo	2.25
	1580	slst, ls, dolo, evap	2.5

OGC #370

Tenneco Federal l-B; T. 10 N., R. 24 E., sec 4; elev. = 6852; lithology log #2065

Formation	Depth to bottom	Lithology	Density
Volcanics	400	volcanics	
Undifferentiated	808	ss, slst, sh	
Moencopi	925		
Kaibab	1022	ls, dolo	
Coconino	1420	ss	
Supai	2220	ss, evap, dolo	2.30-2.40
Fort Apache	2400	dolo, anhyd	2.3
	2850	anhyd, slst, dolo	2.2
	3535	slst, dolo	2.5
Naco	4339	ls, sh, slst	2.60-2.65
Molas	4398	ls, sh	2.30-2.40
Redwall	4490	dolo, ls	2.5
Martin	4570	ls, ss	2.3
Precambrian (?)		ls, ss (?)	

OCC #312
Atlantic Richfield; T. 28 N., R. 15 E., sec 9; elev. = 5808; lithology log #2041

Formation	Depth to bottom	Lithology	Density
Navajo	830	ss, conglomerate (cgl)	
Kayenta	1098	sh, slst, ss	
Moenave	1394	slst, ss, sh	2.35
Wingate	1544	ss, sh, slst	2.20-2.45
Chinle	2050	ss, slst	2.55
	2855	sh, ls	2.35
Shinarump	2923	sh, ss	2.35
Moencopi	3054	sh, slst	2.55
Kaibab	3194	ls	2.60-2.65
Supai	5543	ss, slst	2.65
Naco	5820	ls, sh	2.75-2.80
Horshoe Mesa			
Mooney Falls			
Thunder Springs			
Whitmore Wash	6459	ls, dolo	2.75-2.80
Elbert			
McCracken			
Aneth			
Bright Angel	6480	sh, slst	2.45
Tapeats	6607	ss, slst, cgl	2.65
Precambrian			

OGC #368
Tenneco Oil Fort Apache Tract 56 #l-X; T. 10 N., R. 21 E., sec 31; elev. = 6626; Lithology log #2076

Formation	Depth to bottom	Lithology	Density
Coconino	660	ss	
Supai	1445	sh, ss, evap, dolo	2.35
Fort Apache	1550	ls, dolo	2.55-2.65
	1990	anhyd, dolo, ss, slst	2.35
	3400	ls, dolo, sh	2.50-2.60
Naco	3517	sh, dolo, ls	2.60-2.70
Mississippian	3625	ls	2.65
Martin	3830	sh, dolo, ls	2.75
Cambrian	4040	dolo, sh, ss	
Precambrian		granite, few ferrimagnesium, quartz, microcline	

ILLUSTRATIONS

Figure

1. Isopach of total Paleozoic strata in northeast Arizona (from Peirce et al., 1970, plate 13B).
2. Isopach of lower Paleozoic (combined Cambrian, Devonian, and Mississippian systems) strata (from Peirce et al., 1970, plate 12B).
3. Isopach of upper Paleozoic (combined Pennsylvanian and Permian systems) strata in northeast Arizona (from Peirce et al., 1970, plate 13A).
4. Magnetic Anomaly No. 2 and model of possible source. Flight elevation 9000 feet m.s.l.
5. Holbrook Magnetic Anomaly and model of possible source. Flight elevation 9000 feet m.s.l.
6. Gravity Line 1: In the upper figure the solid dots are the residual gravity values used for the modeling. The x's are the computed values from the gravity effect of the model. The lower figure displays the geology both interpreted and actual along the line. Solid dots are elevations at gravity station locations. Open dots are apparent basement elevations. Stars indicate oil shows in drill holes. Geographic locations and features and drill hole numbers are indicated above the surface elevation profile. The lithology of the basement rocks at the bottom of the drill holes is indicated below the open dots. The stratigraphy has been extrapolated from drill holes. This and all subsequent gravity illustrations are the result of modeling with a constant -0.20g/cc density contrast.

7A. Line 1: Regional Gravity and Bouguer gravity anomaly profiles.

7B. Line 2: Regional and Bouguer Gravity anomaly profiles.

8. Magnetic anomaly No. 3 and model of possible source. Flight elevation 9000 feet m.s.l.
9. The Holbrook Magnetic Anomaly (upper figure) and the Bouguer and residual gravity anomaly (lower figure) and their relationship to the model of the source of the magnetic anomaly are compared.

lO. The observed residual magnetic anomaly (open dots) along Flight Line 85 (Sauck and Sumner, 1970) are compared with the computed magnetic anomaly (closed dots) of the resulting model from Gravity Line l (figure 6).

11. Gravity Line 2: (see explanation for figure 6).
12. Magnetic Anomaly No. 1 and model of possible source.
13. Line 3: Regional and Bouguer Gravity anomaly profiles.
14. Gravity Line 3: (see explanation for figure 6).

15A. Line 4: Regional gravity and Bouguer gravity anomaly profiles.

15B. Line 5: Regional gravity and Bouguer gravity anomaly profiles.

16. Gravity Line 4: (see explanation for figure 6) "Calculated Basement" is result of -0.20g/cc contrast model. "Probable Basement" is the result of a model with 500 feet of -0.50g/cc Puerco River sediments.
17. Gravity Line 5: (see explanation for figure 6).

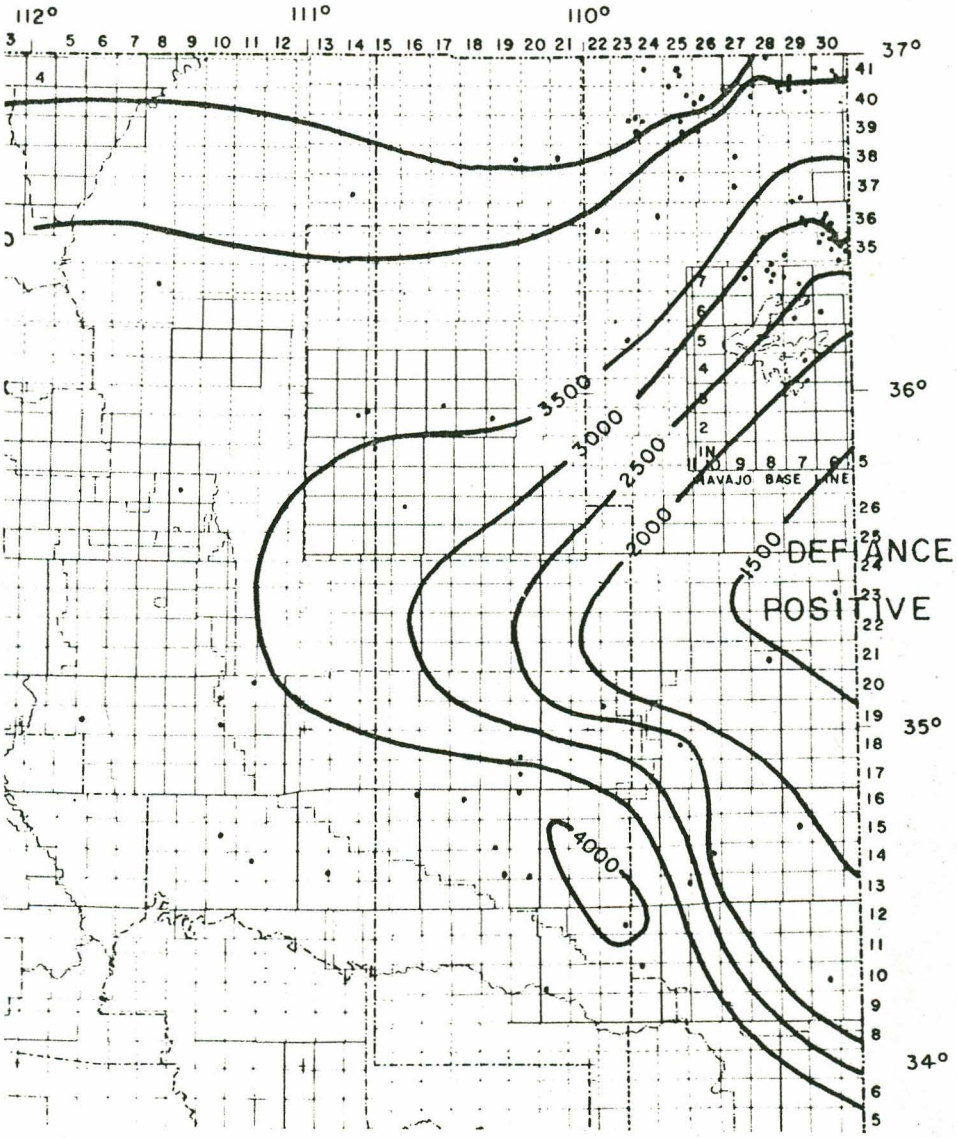
112°
111°
110°
37°
36°
35°
34°
3500
3000
2500
2000
1500
4000
DEFIANCE
POSITIVE
NAVAJO BASE LINE

Figure 1

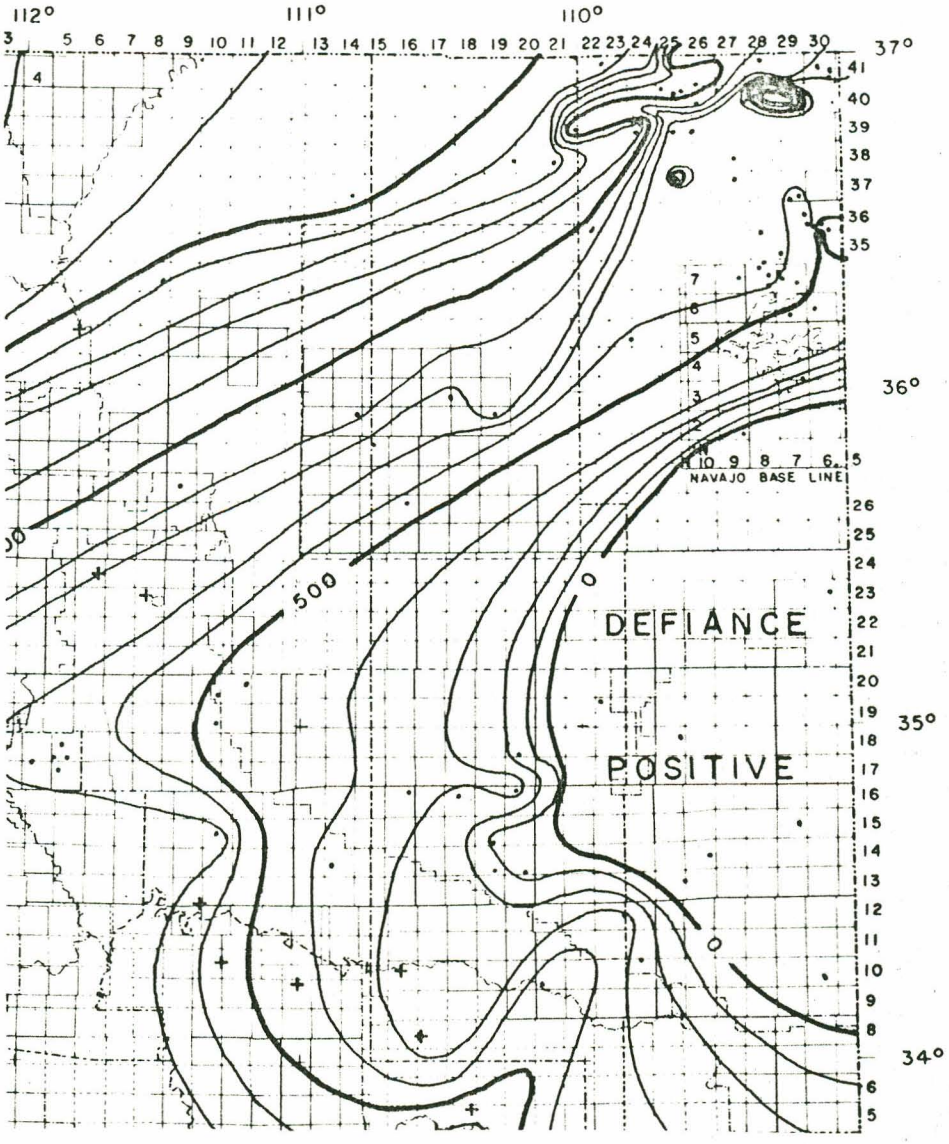
112°
111°
110°
37°
36°
35°
34°
500
0
DEFIANCE
POSITIVE
NAVAJO BASE LINE

Figure 2

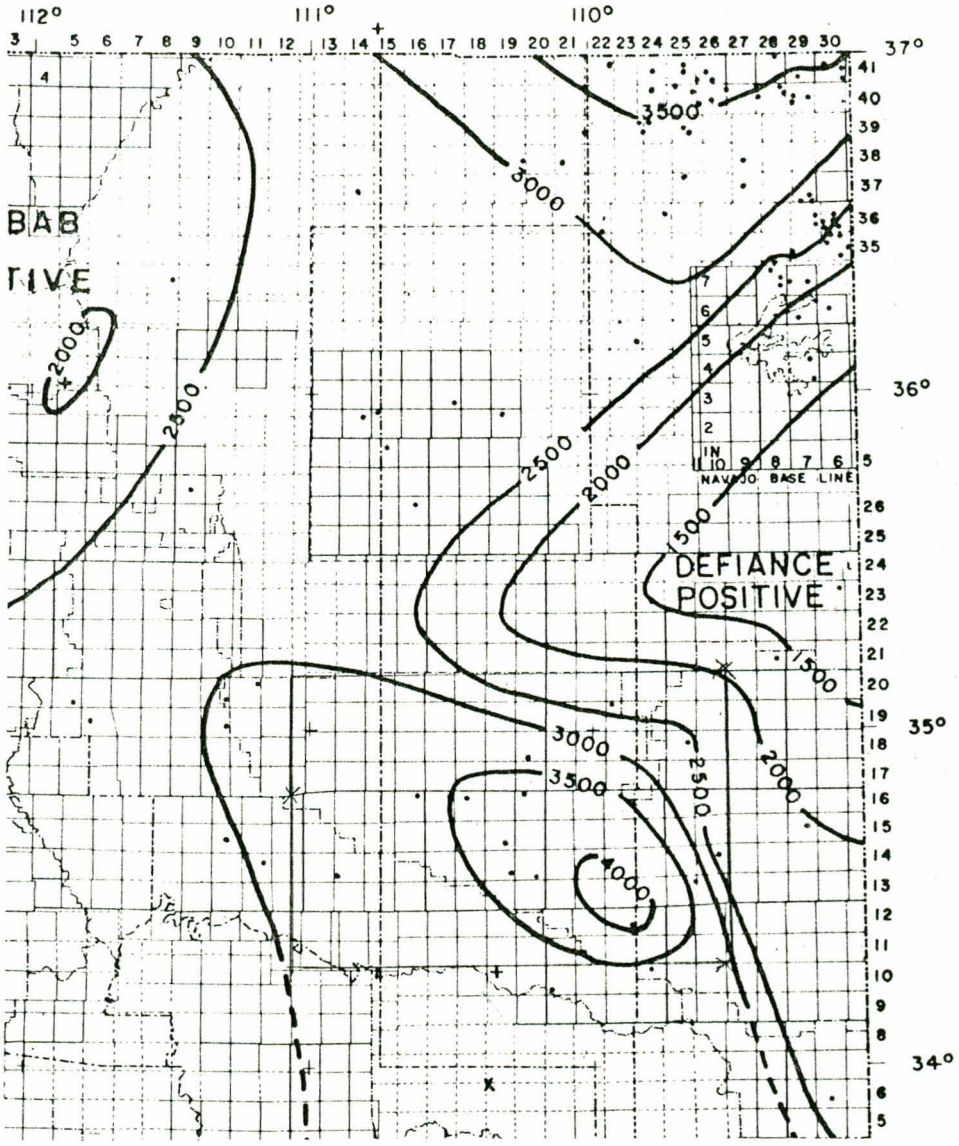
112°
111°
110°
37°
36°
35°
34°
BAB
TIVE
DEFIANCE
POSITIVE
3500
3000
2500
2000
1500
1000
NAVAJO BASE LINE

Figure 3

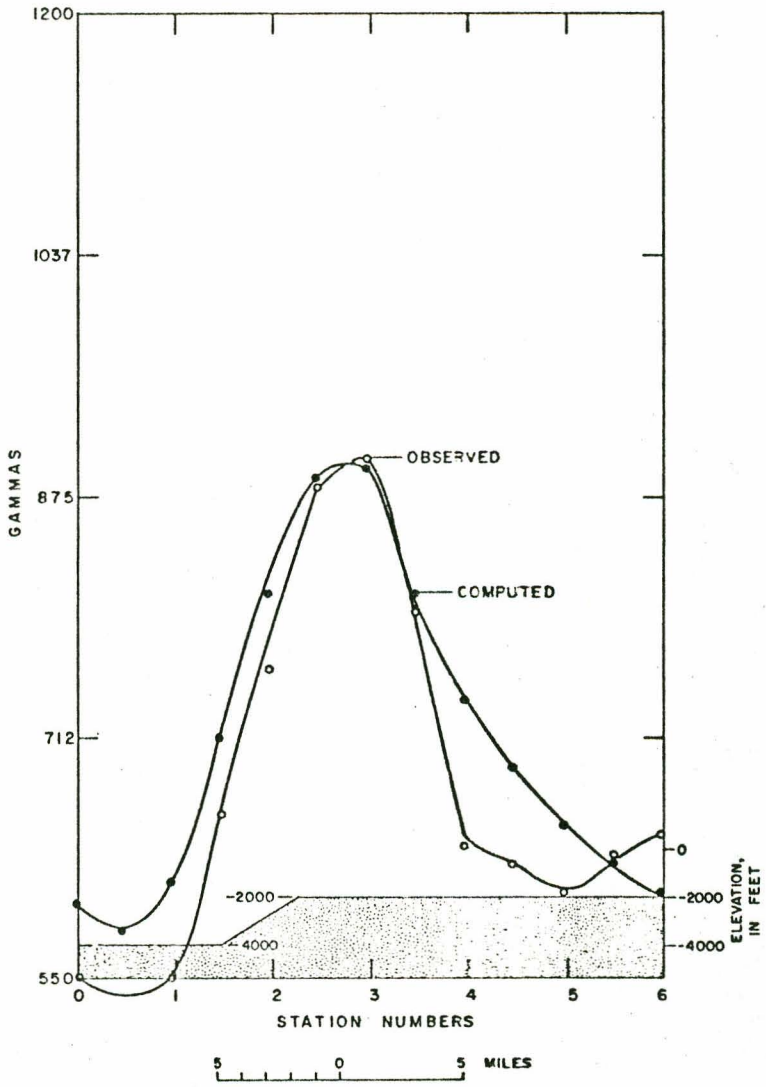
1200
1037
875
712
550
GAMMAS
OBSERVED
COMPUTED
-2000
-4000
0
-2000
-4000
ELEVATION, IN FEET
0
1
2
3
4
5
6
STATION NUMBERS
5
0
5 MILES

Figure 4

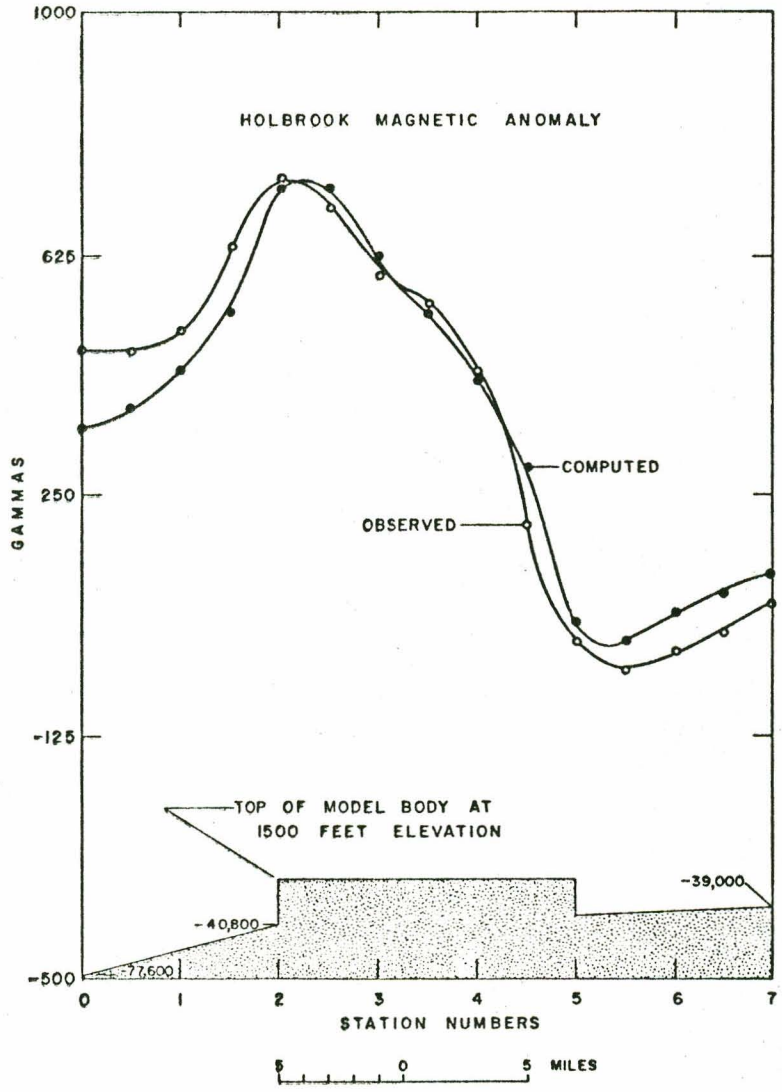
HOLBROOK MAGNETIC ANOMALY
1000
625
250
-125
-500
GAMMAS
COMPUTED
OBSERVED
TOP OF MODEL BODY AT
1500 FEET ELEVATION
-39,000
-40,800
-77,600
0
1
2
3
4
5
6
7
STATION NUMBERS
5
0
5 MILES

Figure 5

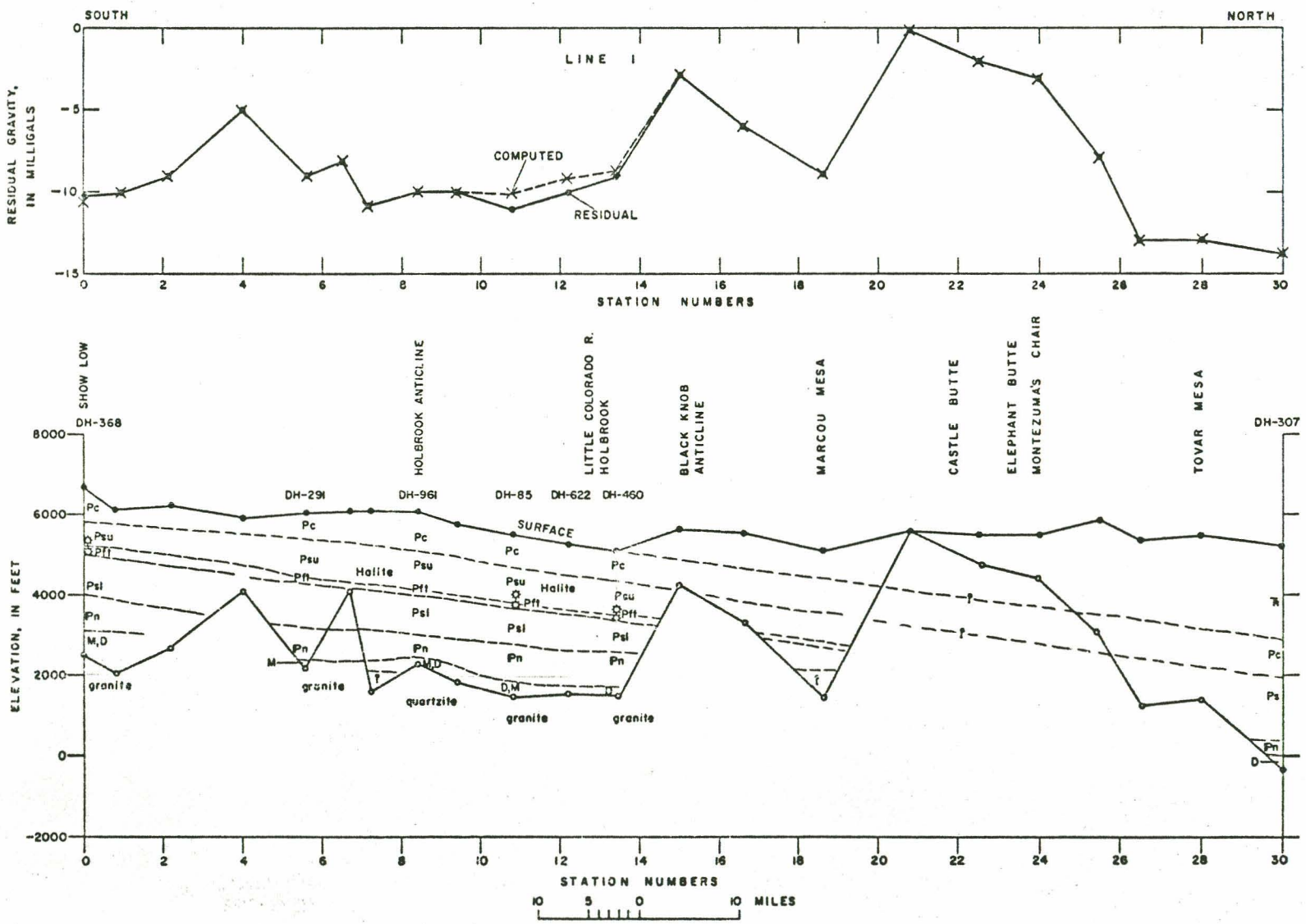
SOUTH
NORTH
LINE I
COMPUTED
RESIDUAL
RESIDUAL GRAVITY, IN MILLIGALS
STATION NUMBERS
SHOW LOW
HOLBROOK ANTICLINE
LITTLE COLORADO R.
HOLBROOK
BLACK KNOB ANTICLINE
MARCOU MESA
CASTLE BUTTE
ELEPHANT BUTTE
MONTEZUMA'S CHAIR
TOVAR MESA
DH-368
DH-291
DH-961
DH-85
DH-622
DH-460
DH-307
SURFACE
Halite
granite
quartzite
ELEVATION, IN FEET
MILES

Figure 6

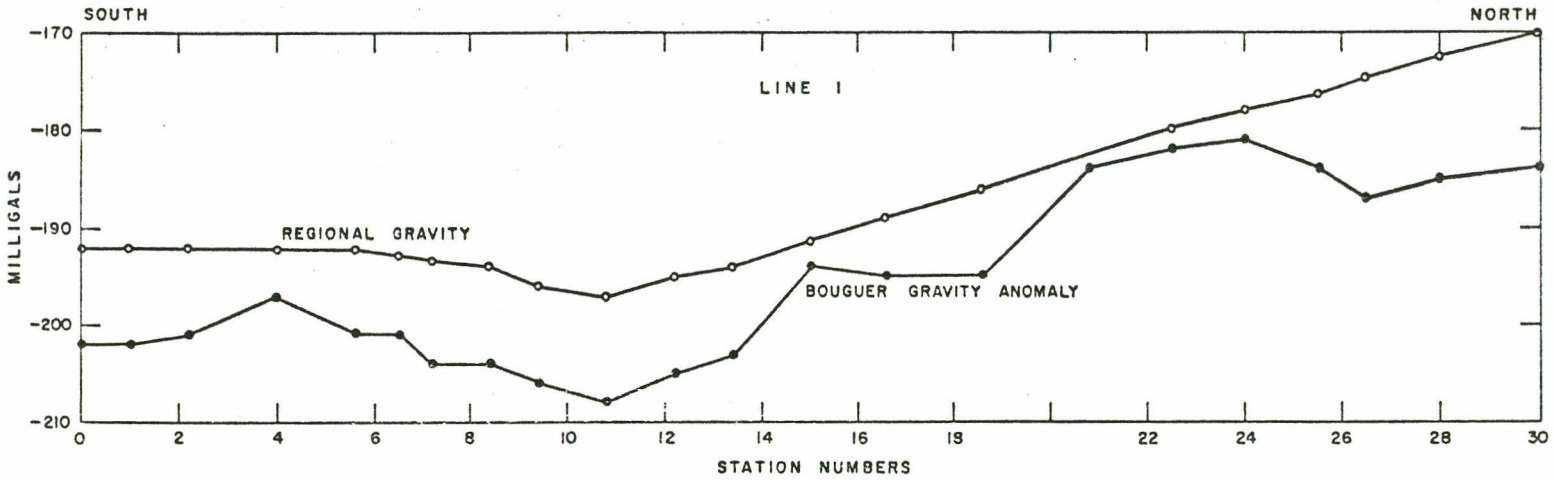

Figure 7A

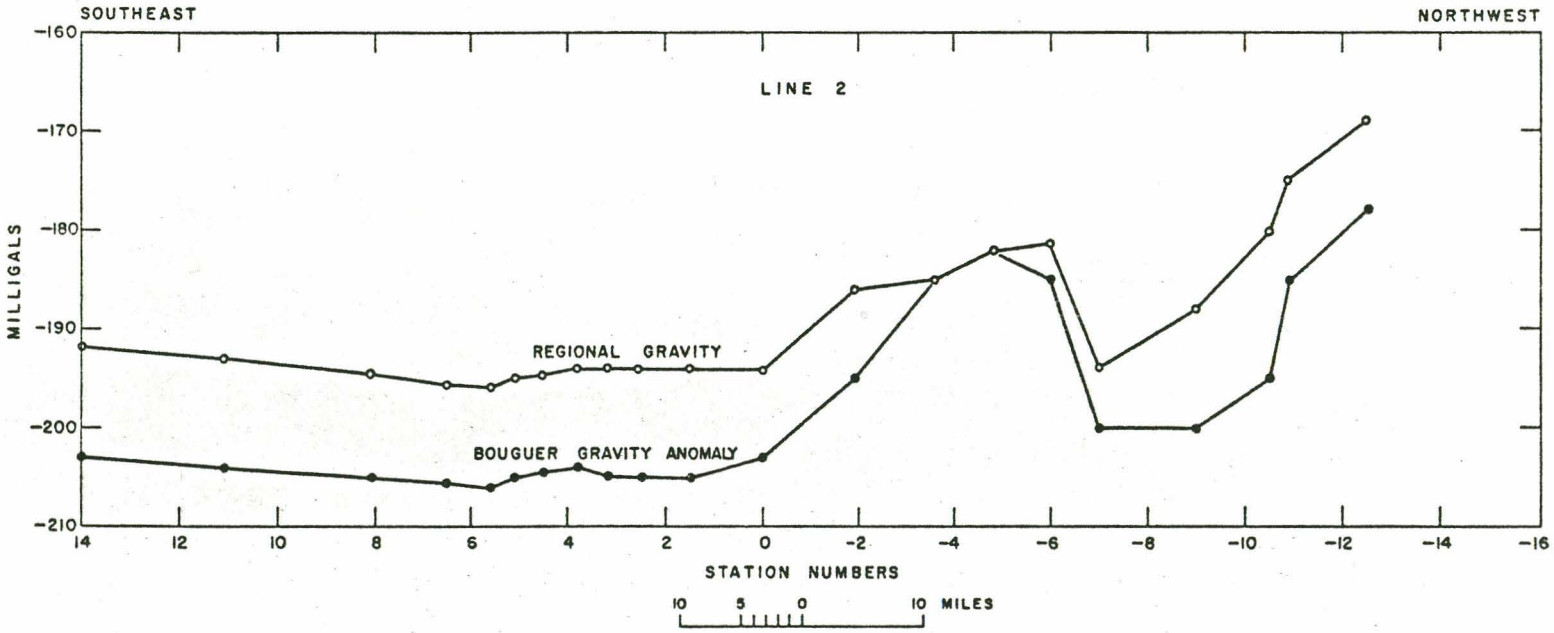

Figure 7B

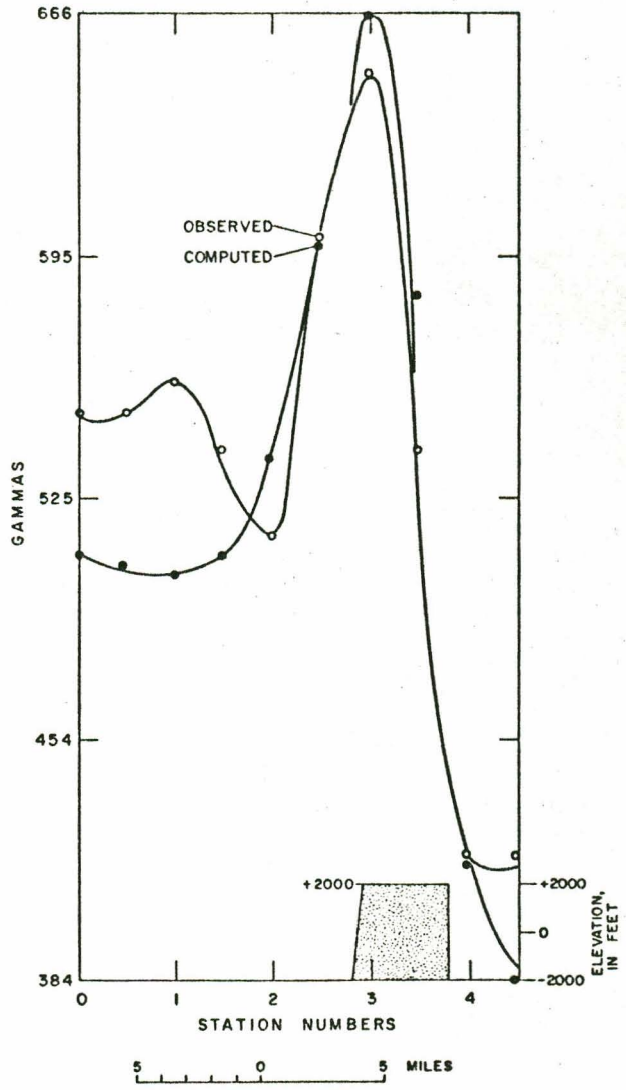
666
595
525
454
384
GAMMAS
OBSERVED
COMPUTED
+2000
+2000
0
-2000
ELEVATION, IN FEET
0
1
2
3
4
STATION NUMBERS
5
0
5
MILES

Figure 8

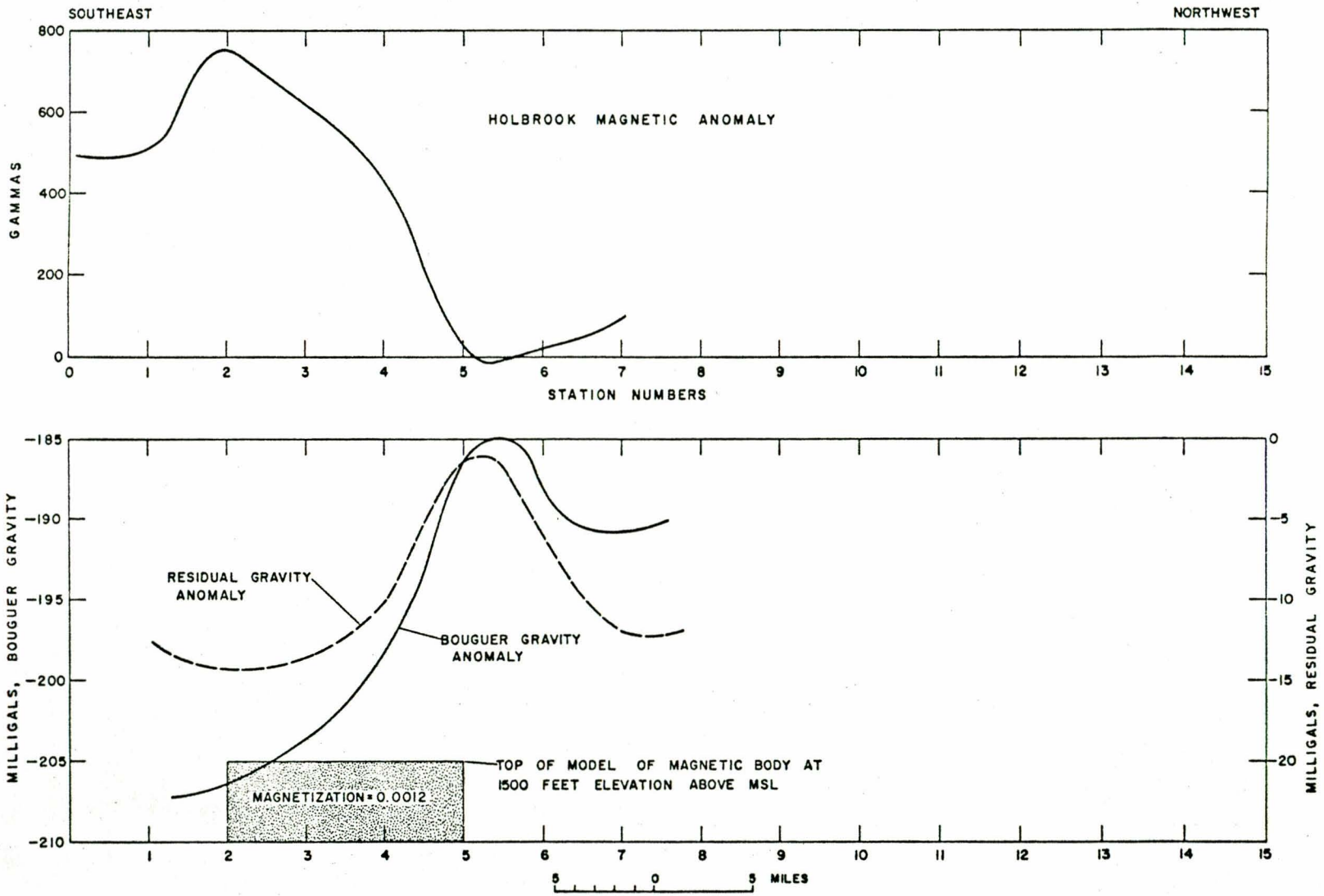
SOUTHEAST
NORTHWEST
HOLBROOK MAGNETIC ANOMALY
GAMMAS
800
600
400
200
0
STATION NUMBERS
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
MILLIGALS, BOUGUER GRAVITY
-185
-190
-195
-200
-205
-210
MILLIGALS, RESIDUAL GRAVITY
0
-5
-10
-15
-20
RESIDUAL GRAVITY ANOMALY
BOUGUER GRAVITY ANOMALY
TOP OF MODEL OF MAGNETIC BODY AT 1500 FEET ELEVATION ABOVE MSL
MAGNETIZATION = 0.0012
5 0 5 MILES

Figure 9

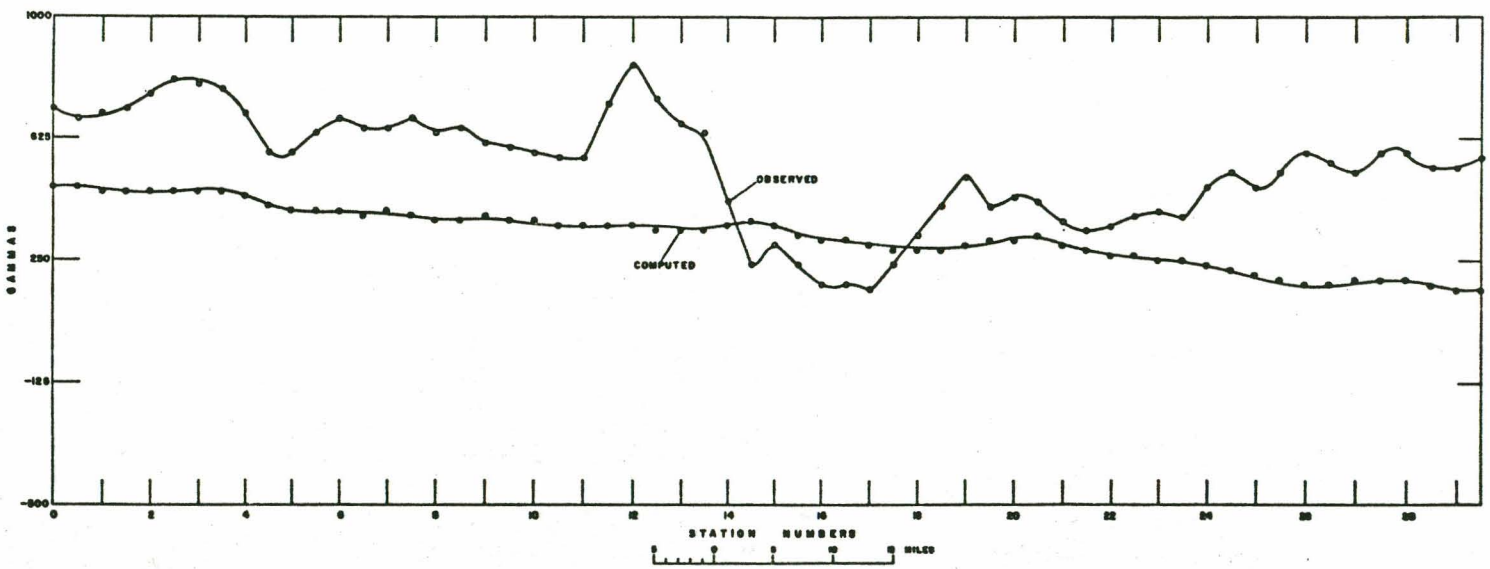
1000
625
250
-125
-500
GAMMAS
OBSERVED
COMPUTED
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
STATION NUMBERS
MILES

Figure 10

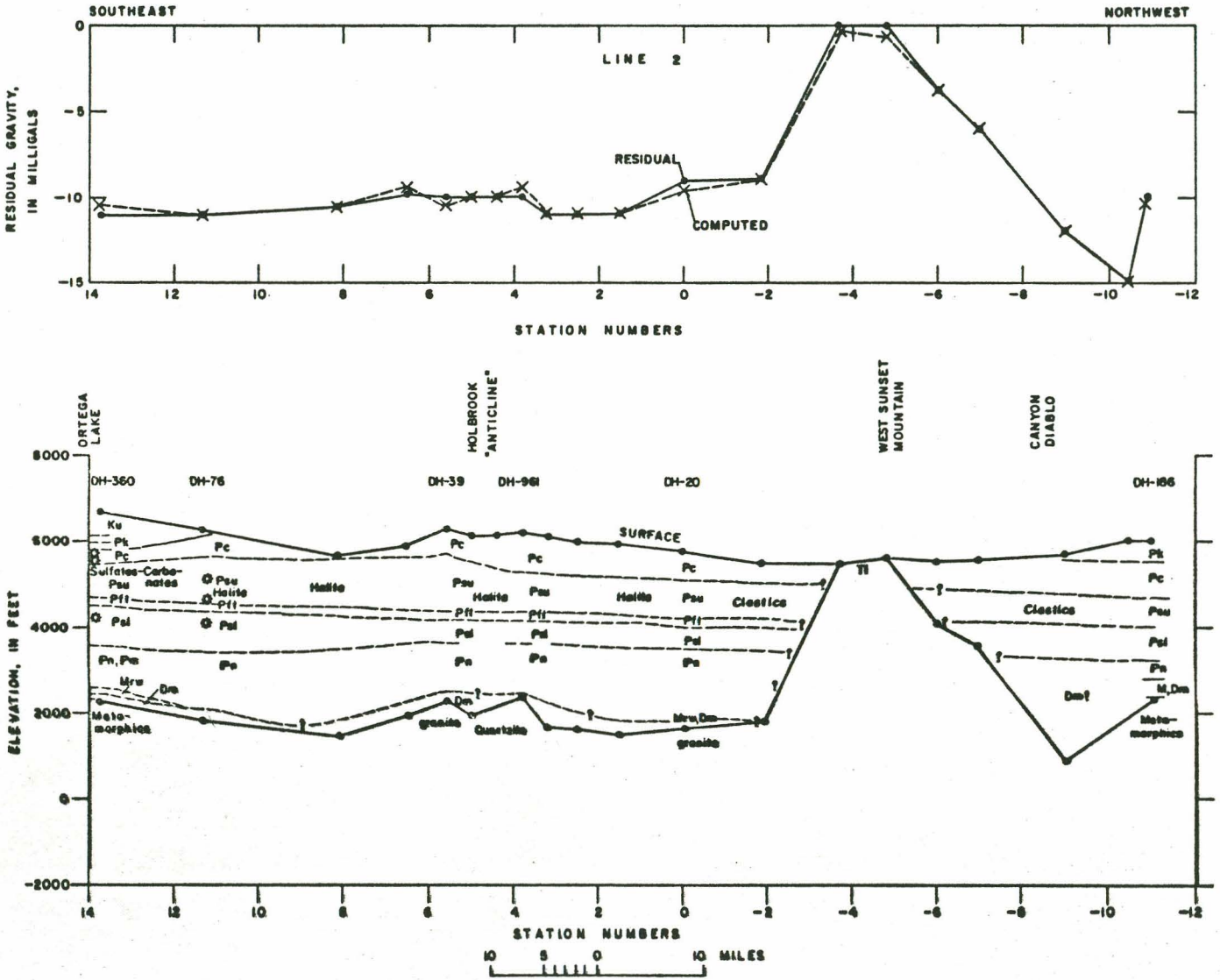
SOUTHEAST
NORTHWEST
LINE 2
RESIDUAL
COMPUTED
RESIDUAL GRAVITY, IN MILLIGALS
STATION NUMBERS
ORTEGA LAKE
HOLBROOK "ANTICLINE"
WEST SUNSET MOUNTAIN
CANYON DIABLO
DH-360
DH-76
DH-39
DH-96I
DH-20
DH-166
SURFACE
Sulfates-Carbonates
Halite
Clastics
Metamorphics
granite
Quartzite
ELEVATION, IN FEET
STATION NUMBERS
10 5 0 10 MILES

Figure 11

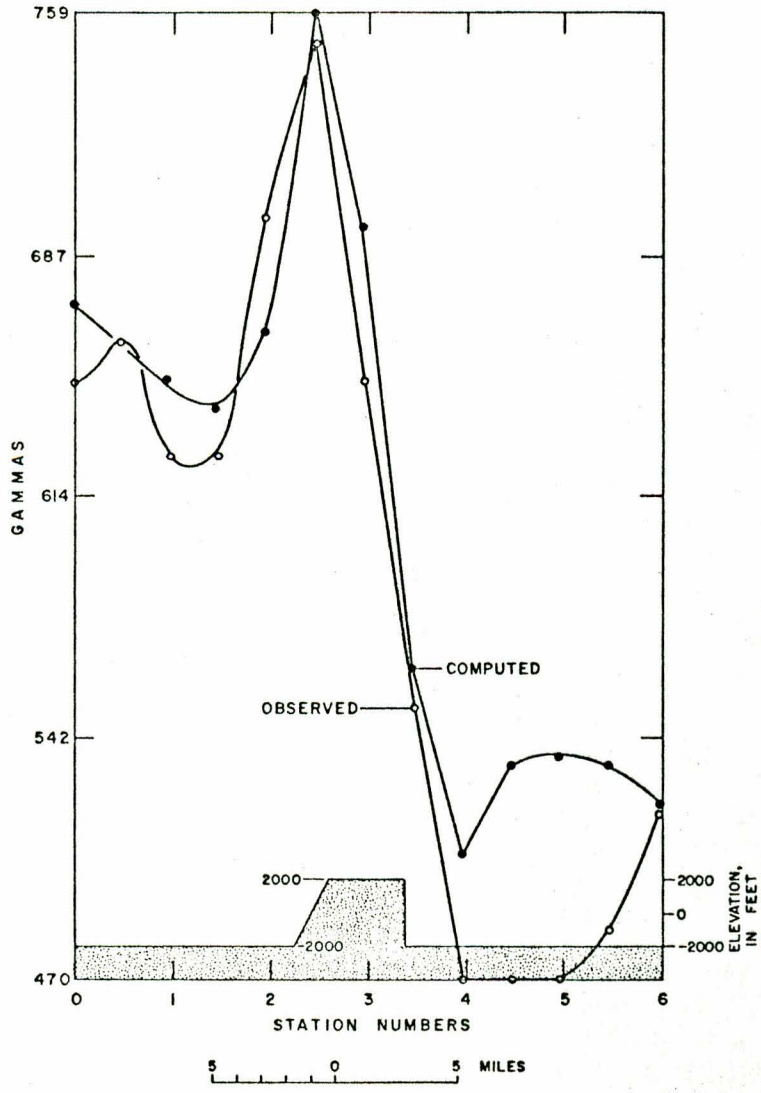
759
687
614
542
470
GAMMAS
COMPUTED
OBSERVED
2000
-2000
2000
0
-2000
ELEVATION, IN FEET
0
1
2
3
4
5
6
STATION NUMBERS
5
0
5
MILES

Figure 12

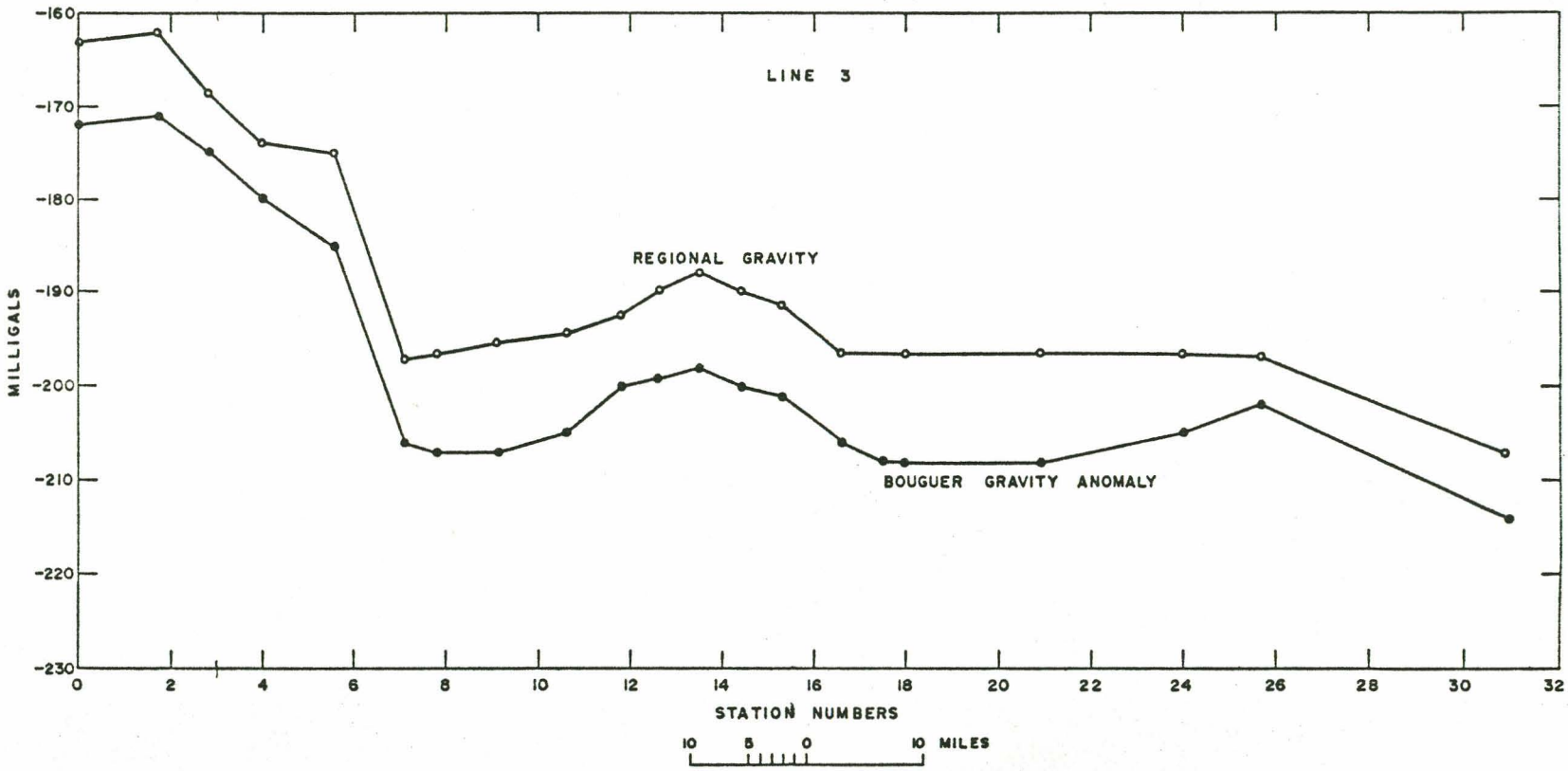
LINE 3
REGIONAL GRAVITY
BOUGUER GRAVITY ANOMALY
MILLIGALS
-160
-170
-180
-190
-200
-210
-220
-230
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
STATION NUMBERS
10 5 0 10 MILES

Figure 13

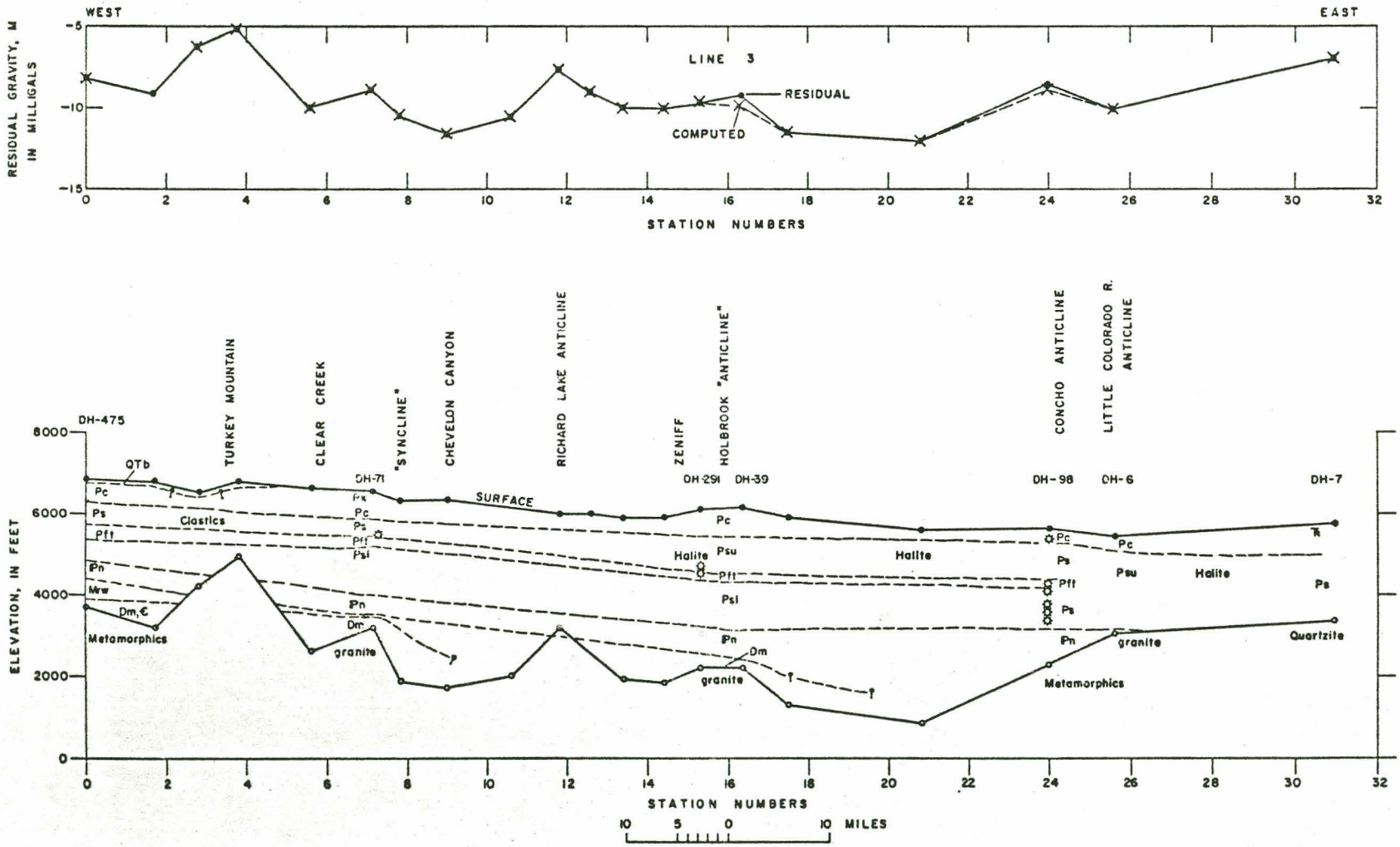
WEST
EAST
LINE 3
RESIDUAL
COMPUTED
RESIDUAL GRAVITY, M IN MILLIGALS
STATION NUMBERS
TURKEY MOUNTAIN
CLEAR CREEK
"SYNCLINE"
CHEVELON CANYON
RICHARD LAKE ANTICLINE
ZENIFF
HOLBROOK "ANTICLINE"
CONCHO ANTICLINE
LITTLE COLORADO R. ANTICLINE
DH-475
DH-71
DH-291
DH-39
DH-98
DH-6
DH-7
SURFACE
QTb
Clastics
Metamorphics
granite
Halite
Quartzite
ELEVATION, IN FEET
MILES

Figure 14

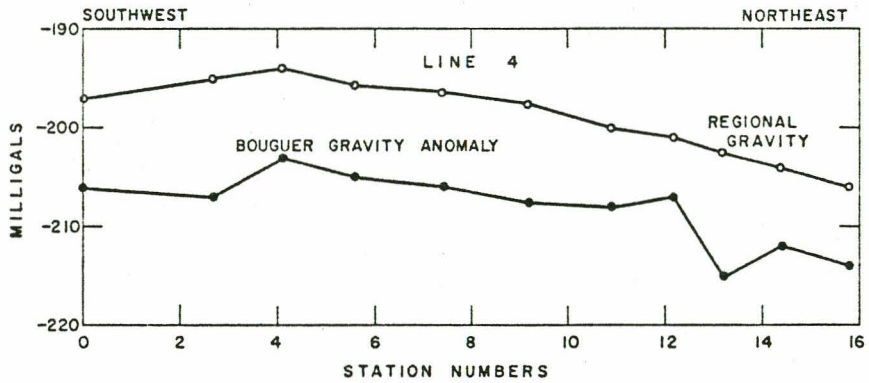

Figure 15 A

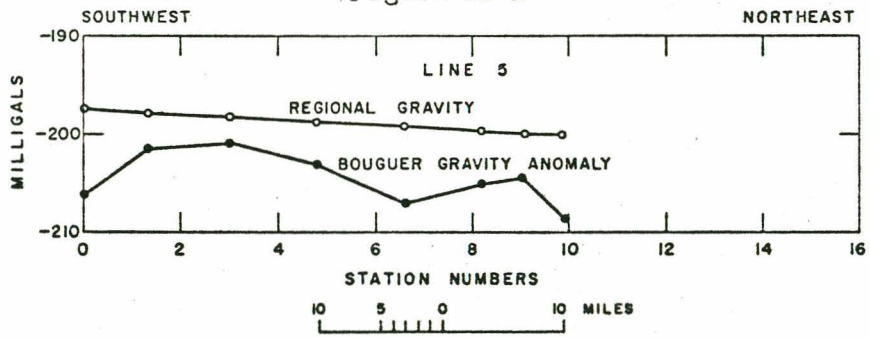

Figure 15 B

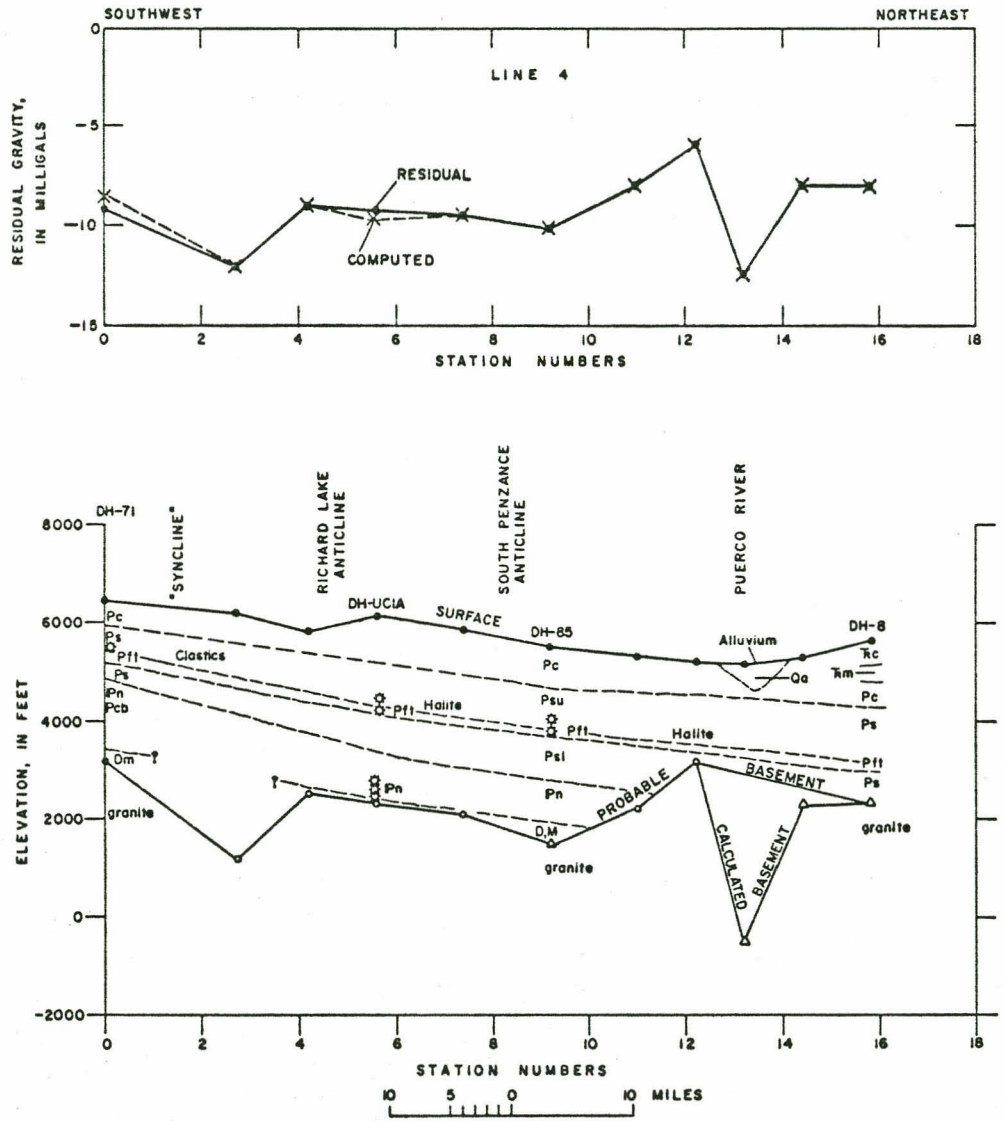
SOUTHWEST
NORTHEAST
LINE 4
RESIDUAL GRAVITY, IN MILLIGALS
RESIDUAL
COMPUTED
STATION NUMBERS
DH-71
"SYNCLINE"
RICHARD LAKE ANTICLINE
SOUTH PENZANCE ANTICLINE
PUERCO RIVER
DH-UCIA
SURFACE
DH-85
DH-8
Alluvium
Qa
Clastics
Halite
PROBABLE BASEMENT
CALCULATED BASEMENT
granite
ELEVATION, IN FEET
STATION NUMBERS
MILES

Figure 16

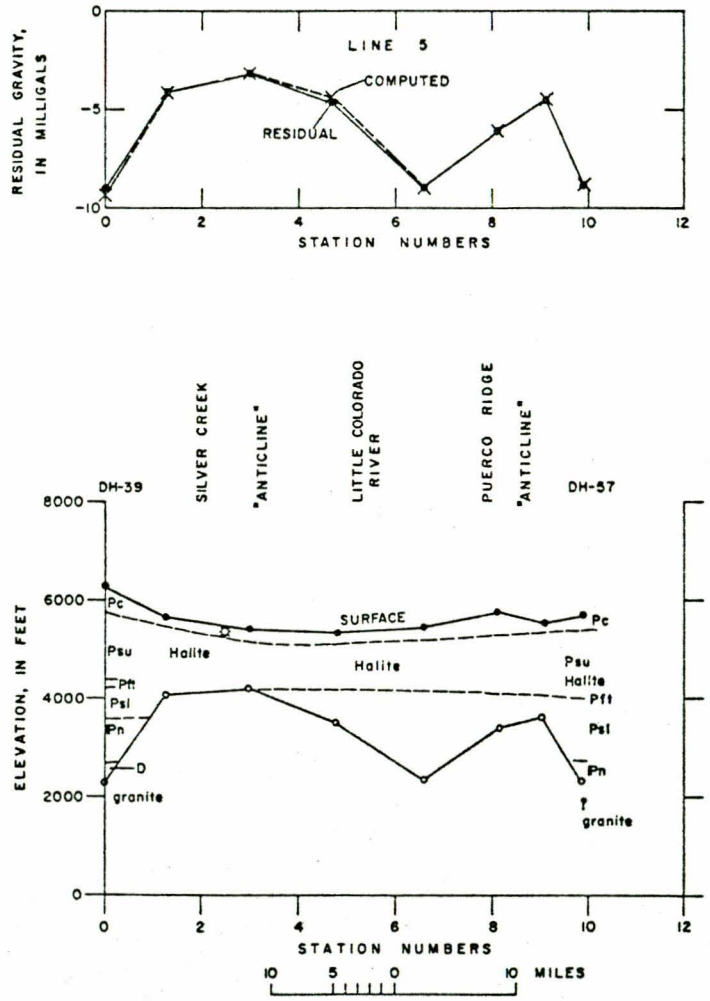
LINE 5
COMPUTED
RESIDUAL
RESIDUAL GRAVITY, IN MILLIGALS
0
-5
-10
0
2
4
6
8
10
12
STATION NUMBERS
SILVER CREEK
"ANTICLINE"
LITTLE COLORADO RIVER
PUERCO RIDGE
"ANTICLINE"
DH-39
DH-57
8000
6000
4000
2000
0
ELEVATION, IN FEET
Pc
SURFACE
Pc
Psu
Halite
Halite
Psu
Halite
Pft
Psl
Pn
D
granite
Pft
Psl
Pn
granite
STATION NUMBERS
10
5
0
10 MILES

Figure 17