UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Regional magnetic and gravity features of the Gibson Dome area and surrounding region, Paradox Basin, Utah: A preliminary report

by

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Abstract

Analyses of regional gravity and magnetic anomaly maps have been carried out to assist in the evaluation of the Gibson Dome area as a possible repository site for high-level radioactive waste. Derivative, wavelength-filtered, and trend maps were compiled to aid in properly locating major geophysical trends corresponding to faults, folds, and lithologic boundaries. The anomaly maps indicate that Paradox Basin is characterized by a heterogeneous Precambrian basement, essentially a metamorphic complex of gneisses and schist intruded by granitic rocks and mafic to ultramafic bodies. Interpreted Precambrian structures trend predominantly northwest and northeast although east-west trending features are evident. Prominent gravity lows define the salt anticlines. Structural and lithologic trends in the Gibson Dome area are closely examined. Of greatest interest is a series of circular magnetic highs trending west-northwest into the Gibson Dome area. Further study of the exact definition and geologic significance of this series of anomalies is warrented.

Introduction

The Department of Energy is responsible for determining or identifying geographic areas within the United States to safely isolate high-level radioactive waste. The Department is undertaking the program's management and technical direction through the Office of Nuclear Waste Isolation. By way of interagency agreements, the U.S. Geological Survey is assisting in this difficult task. Preliminary analyses of geophysical and geological data suggest that the Gibson Dome area in Paradox Basin, Utah, may be a feasible repository site. This report deals with a regional magnetic and gravity study (interagency agreement number DE-A197-79ET44711) to aid in the concerted effort of evaluating the Gibson Dome site.

Gravity and magnetic data sets have been assembled for a region extending radially for a distance of about 80 km around Gibson Dome (fig. 1). Our task in interpreting these potential field data has been to delineate variations in lateral composition within the sedimentary sequence and lithologic and structural trends in Precambrian basement. Derivative, wavelength filtered, and trend maps have been compiled to properly identify and locate geophysical features. Discussions are given on interpreted regional features and their possible implications in selecting Gibson Dome as a repository site.

Gibson Dome is located in the west-central portion of Paradox Basin, a middle Pennsylvanian tectonic feature lying within the Colorado Plateau (fig. 1). Paradox Basin has experienced a long and complex history, resulting in the formation of major geologic features with complex lithologies and structures (Shoemaker, 1954; Hite, 1968). It is regionally characterized by salt anticlines and huge monoclinal uplifts separated by structural terraces and basins. Precambrian basement is and markedly heterogeneous, consisting of a wide variety of granites, schists, gneisses, and mafic intrusive rocks (Case, 1966; Case and Joesting, 1972a). Some of these lithologic discontinuities have structural origin. Overlying crystalline basement are Paleozoic carbonates, clastics, and evaporites that may exceed 5200 m in aggregate thickness. At least 1500 m of Mesozoic marine sandstones and shales and continental red beds are present. High laccolithic mountains, composed of diorite porphyry and associated rocks, were formed during Late Cretaceous

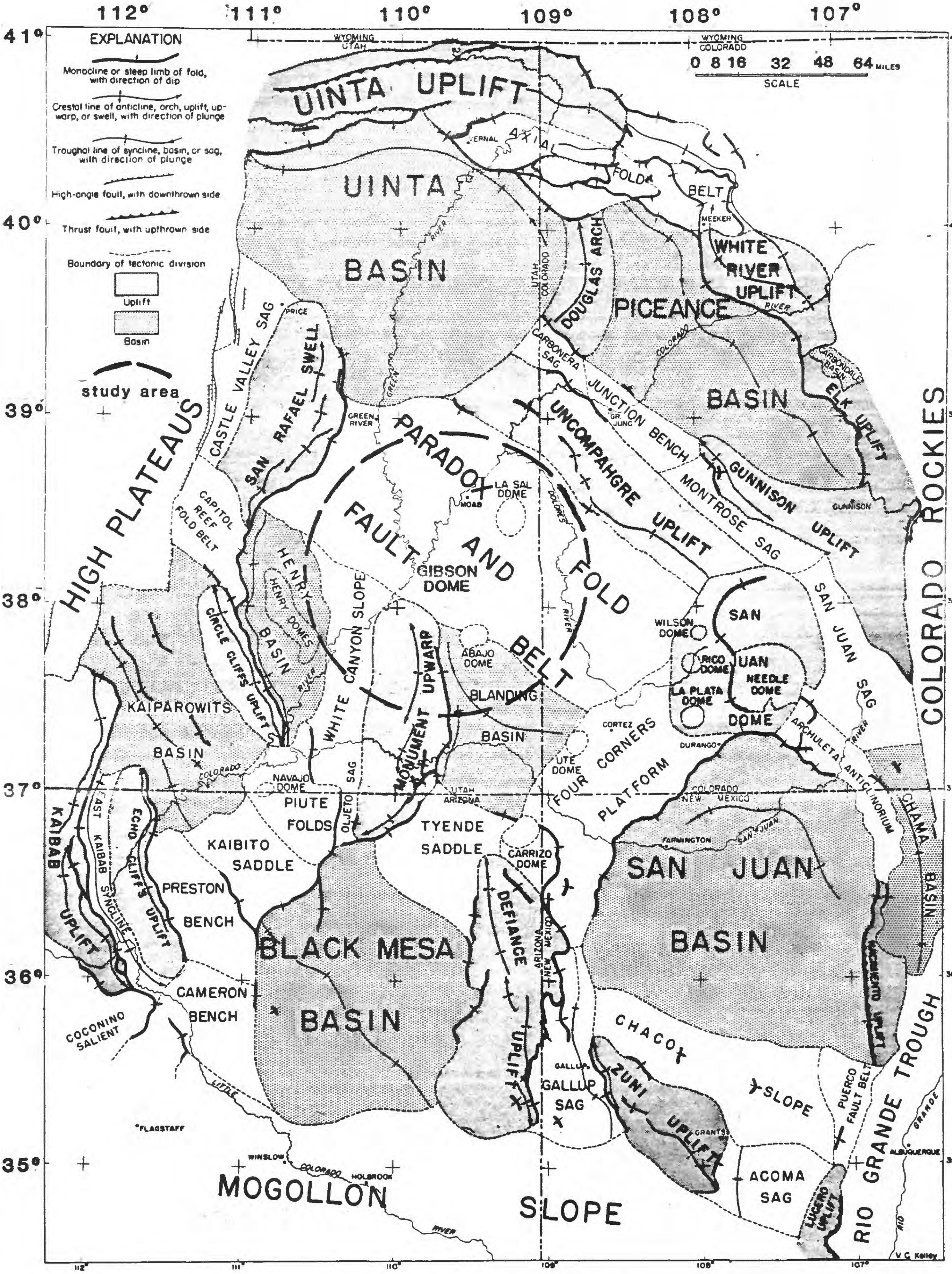


figure 1.– TECTONIC DIVISIONS OF THE COLORADO PLATEAU
(from Four Corners Geological Society guidebook, 3rd Field Conf., 1960)

time. The structural and lithologic complexities of Paradox Basin become evident in the interpretation of gravity and magnetic data.

Correlation of magnetic, gravity, and geologic data provides information on Precambrian lithologic and structural boundaries, on depth to Precambrian basement, and on lateral compositional variations of the sedimentary column above basement. Delineation of salt anticlines and igneous intrusions within Paradox Basin is especially adapted to the gravity method because major density contrasts are involved. Compositional and structural trends in Precambrian crystalline basement readily produce identifiable anomalies in the magnetic field as a result of sufficient contrasts in associated magnetizations. These geophysical observations are documented by Byerly and Joesting (1959), Case (1966), Case and Joesting (1961), Case and others (1963), Joesting and Byerly (1956, 1958), Joesting and Case (1962), and Joesting and others (1966) in their gravity and magnetic studies of subregions within Paradox Basin. Utilizing the results of these studies of localized areas, Case and Joesting (1972a) provided an extensive regional study of Paradox Basin by correlating gravity, magnetic, and geologic data. The present report discusses the findings of these previous investigators as well as new structural information indicated on the anomaly maps and related filtered-anomaly maps.

Gravity Data

Coverage

The bulk of the gravity anomaly data (4453 stations) was extracted from the U.S. Department of Defense (DoD) gravity-data files available through the U.S. National Oceanic and Atmospheric Administration (NOAA) Data Center (National Geophysical and Solar Terrestrial Data Center Boulder, Colorado, 80302). Additional gravity data (692 stations) were kindly furnished by G. R. Keller and Carlos Aikens, University of Texas. This latter data set was not available during the earlier gravity studies by Byerly, Case, and Joesting. The resulting data set contains principal facts (observed gravity, elevation, latitude, and longitude) for 5145 stations with locations shown in plate 1.

When closely inspecting the locations of gravity data with those used by Case and Joesting (1972a), we found however approximately 500 stations absent from our data set. These additional stations are presently being assembled by having them retyped from tables in Case and Joesting (1972b). Because the bulk of these missing stations are located in the region of Uncompahgre Uplift (northeast corner of plate 1), gravity features of this region cannot be delineated with certainty using the compiled gravity-anomaly maps. Nevertheless, thorough discussions of gravity anomalies over the Uncompahgre Uplift are given by Case (1966) and Case and Joesting (1972a) and are summarized in this report. The few remaining missing stations are dispersed throughout the study area; exclusion of these data will not affect our interpretations of gravity features.

Gravity coverage is not uniform. Adequate coverage for regional interpretations is present within the study area except for those regions near the west central part and at the four corners of plate 1. Regional interpretations require a station spacing such that the gradients and amplitudes of all major gravity features are suitably defined for their delineation and for properly locating their position. Of particular interest is the poor coverage in the immediate vicinity of Gibson Dome (fig. 2). Woodward-Clyde Consultants, San Francisco, subcontracted as the Geologic Project Manager of the Paradox Basin study, have purchased proprietary data in the Gibson Dome area with locations shown in figure 3. It should be noted that the processing procedures of these proprietary data (including Bouguer reduction density) are unknown and that the usefulness of these data is, therefore, very limited. Woodward-Clyde Consultants are also presently purchasing additional proprietary gravity data in the Gibson Dome area. It is apparent that nonproprietary gravity stations need to be occupied to insure reliable identification and modeling results of features in the Gibson Dome region. The locations of proprietary data and the structural information delineated from these data should be used to plan new gravity surveys for obtaining maximum control and thus higher resolution in interpreting the data.

The required coverage for detailed analyses of gravity data in a more localized area near Gibson Dome needs to be addressed because of the important objectives of the ongoing Paradox Basin studies. Approximately 200 gravity measurements distributed throughout the area shown in figure 2 should be made to obtain uniform coverage of nonproprietary data. The resulting coverage will be adequate for defining and locating gravity features and for three-dimensional modeling to determine generalized depths to major density discontinuities.

Detailed quantitative analyses will require measurements along profiles selected to obtain maximum information on subsurface features. Placement of these profiles, so that they cross or partially coincide with existing seismic and resistivity profiles, will result in higher resolution in interpretational models derived from all these geophysical methods. Selecting profiles so that they cross drill-hole locations will take advantage of geologic information. We estimate about 200-300 stations located along profiles need to be occupied. Survey specifications should include (1) stations every 305 m, (2) anomaly values accurate to within 0.1 mgal, (3) elevation accuracy of ±0.3 m and horizontal location to within ±15 m, and (4) all stations occupied within closed loops. Gravity measurements made in the described manner will supply substantial information on the depths, sizes, shapes, and density contrasts of underlying mass inhomogeneities.

Reduction

Editing of the gravity data involved two steps. In the first step removal of stations having obvious gravity value errors was carried out using the justification that their large gravity amplitudes precluded validity by close inspection of amplitudes of neighboring stations. The second step which involved a considerably larger amount of editing time, included detecting stations with gravity values that produced moderately large distortions or deflections in the gravity contours (i.e. single-station anomalies) and then verifying on topographic maps if the reported station elevations were correct. A station was deleted from the data set if there was a noticeable discrepancy between the station elevation and that indicated on the topographic maps. Elevation errors can occur from entering wrong elevations or station locations. The steps taken to remove erroneous gravity values are considered adequate for a regional study although further discussions on the accuracy of the data are given below.

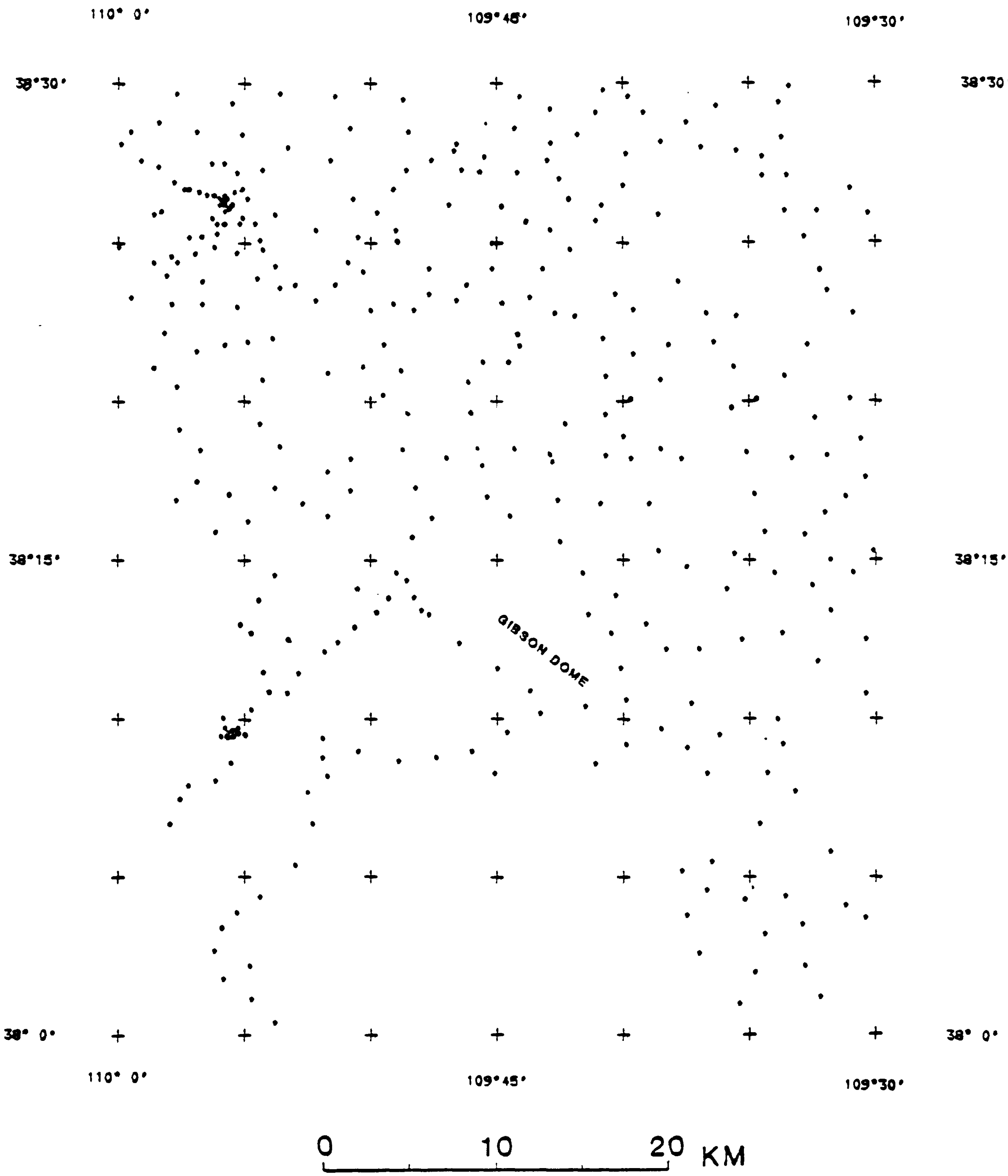


figure 2.-NON PROPRIETARY GRAVITY STATIONS IN THE GIBSON DOME REGION

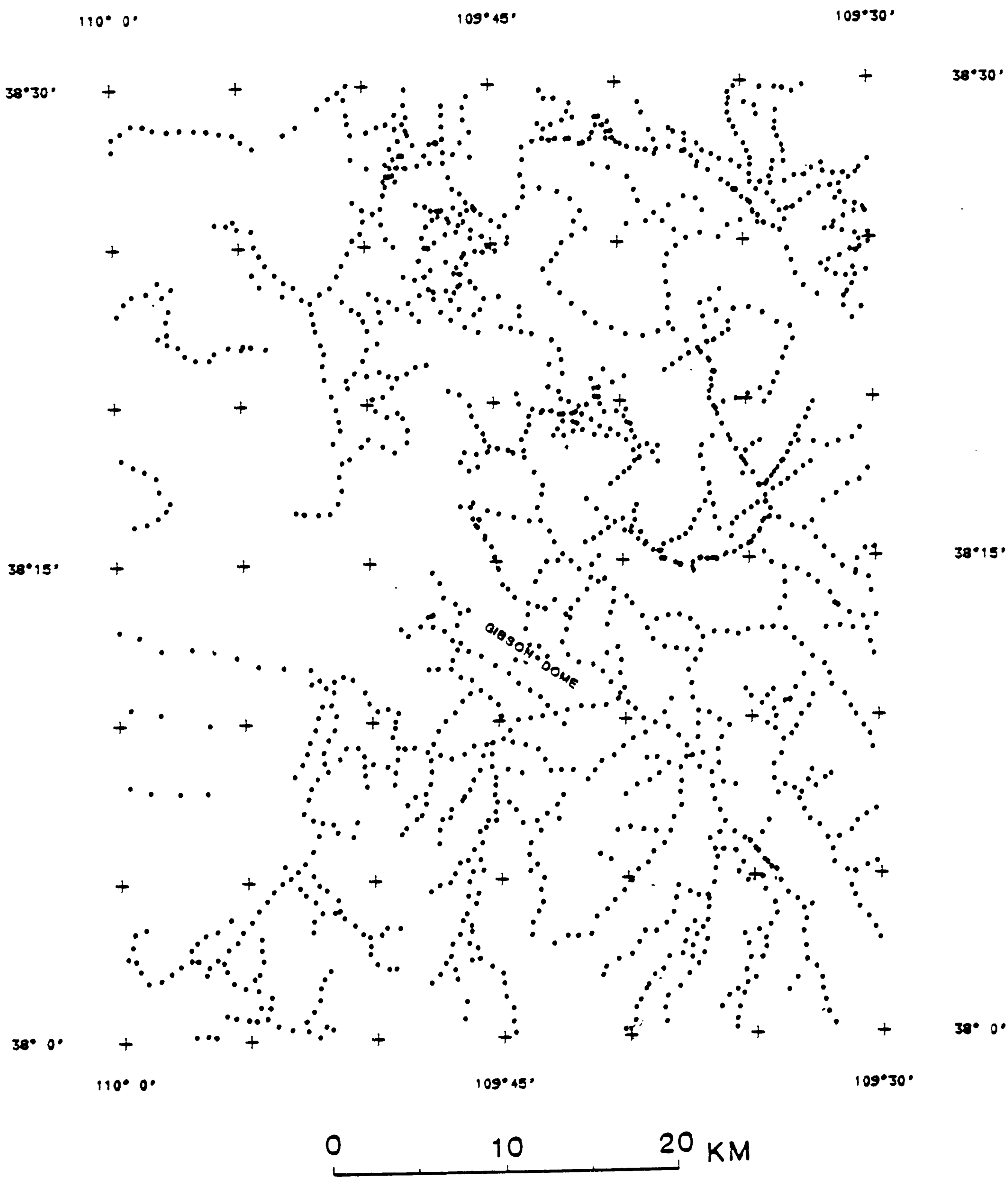


figure 3.-PROPRIETARY GRAVITY STATIONS IN THE GIBSON DOME REGION

Observational gravity measurements detect changes in the magnitude of the Earth's gravitational field. Observed gravity values of the compiled data set have been adjusted to conform to the International Gravity Standardization Net of 1971 (Morelli, 1974). The Bouguer anomaly is commonly determined to study subtle gravity effects related to geologic structures in the crust and upper mantle. To obtain the Bouguer anomaly allowance is made for the change in gravity with latitude and height and for the attraction of topography. For this study Bouguer gravity anomaly values have been computed using the 1967 gravity formula (International Association of Geodesy, 1967) and a reduction density of 2.5 g/cm^3; the equations and related expansions are given by Cordell and others (1982). The selected reduction density of 2.5 g/cm^3 was determined by Byerly, Case, and Joesting to adequately represent density of surficial rocks in Paradox Basin.

Terrain corrections were made utilizing a computer program by Plouff (1977) and digital terrain data for the conterminous United States gridded at an interval of 30" of latitude and longitude (about 0.8 km). The region extending radially from 0.895 to 167 km from each gravity station was used in making a terrain correction. Corrections were generally between 0.1 and 5 mgals, but 22 stations required a terrain correction greater than 20 mgal. A maximum terrain correction of 46.2 mgals occurred at Mt. Peale (elevation = 3877 m) in the La Sal Mountains. The error in omitting terrain corrections from the inner zone (0.0 to 0.895 km) is discussed later.

A data set on a 0.75 km grid was derived from the irregularly spaced Bouguer anomaly values by means of a minimum curvature interpolation method (Webring, 1981). The data were plotted on a Universal Tranverse Mercator (UTM) projection with a central meridian of 111°W. The resulting Bouguer anomaly contour map is given in plate 1.

Accuracy of Bouguer anomaly values

Because of the diverse source of gravity data and thus field procedures, estimation of Bouguer anomaly errors is difficult. For instance, sources of error which depend highly upon field instrumentation and procedure, occur from erroneous observed gravity values, station locations, and elevations. Errors in observed gravity due to gravimetric drift are regarded to be small, generally less than 0.3 mgal with respect to the base station (Case and Joesting, 1972a). Positional errors are thought to generate errors in Bouguer anomaly values of generally less than 0.2 mgals. On the other hand, large errors of 2.4 mgals may be associated with 12.2 m inaccuracies in elevation determined from altimetric traverses. Case and Joesting (1972a) estimate, however, that elevations are generally correct to within 6.1 m, equivalent to errors in Bouguer anomalies of 1.2 mgal or less. From the above consideration of observed gravity, station location, and elevation, one can conclude that they result in errors usually less than 1.7 mgal but may be much larger.

Another source of error in Bouguer anomaly values pertains to improper or inadequate terrain corrections which occur in data reduction. For the present gravity study terrain corrections were made for the region extending radially from 0.895 to 167 km from each station. Corrections to a distance of 167 km will result in small anomaly errors related to outer terrain correction. By ignoring the inner zone correction from 0.0 to 0.895 km, we assumed that the gravity stations occur in the middle of circular regions, 1.8 km in diameter, where surface relief is relatively small. Some stations are, however, located in deep canyons or at the edge of high mesas and thus will have a systematic error associated with their terrain correction. Close inspection of Bouguer anomaly values and their location on topographic maps indicates that ignoring the inner zone terrain correction results in anomaly errors generally less than 2 mgal. The magnitude of this error may increase in extremely rugged terrain.

In comparing plate 1 with the complete Bouguer anomaly map compiled by Case and Joesting (1972a), few discrepancies in anomaly patterns exist within regions containing equivalent station density. Plate 1 exhibits more small-amplitude, short-wavelength anomalies due primarily to the omission of inner zone terrain corrections. Except within regions of poor coverage, the quality of the Bouguer anomaly map (plate 1) is sufficient for a generalized study of regional lithologic and structural boundaries in Paradox Basin.

Future detailed gravity studies in a localized region around Gibson Dome must include further processing of the data that involves additional editing and more complete terrain corrections. The major sources of error in Bouguer anomaly values are related to elevation and terrain correction. The method of obtaining elevation and its accuracy at each station must be evaluated; stations with associated elevation errors greater than about 3 m need to be eliminated or their elevation corrected. Methods are available for obtaining inner zone terrain corrections in an efficient and timely manner. Approximately 15 man minutes per station is required to compute this correction. Application of these two additional steps in the data reduction process will result, for the most part, in Bouguer anomaly values accurate to within 1 mgal. Higher accuracy will certainly be achieved for new stations occupied where relatively smaller errors in gravity readings, elevation, and station location can be maintained.

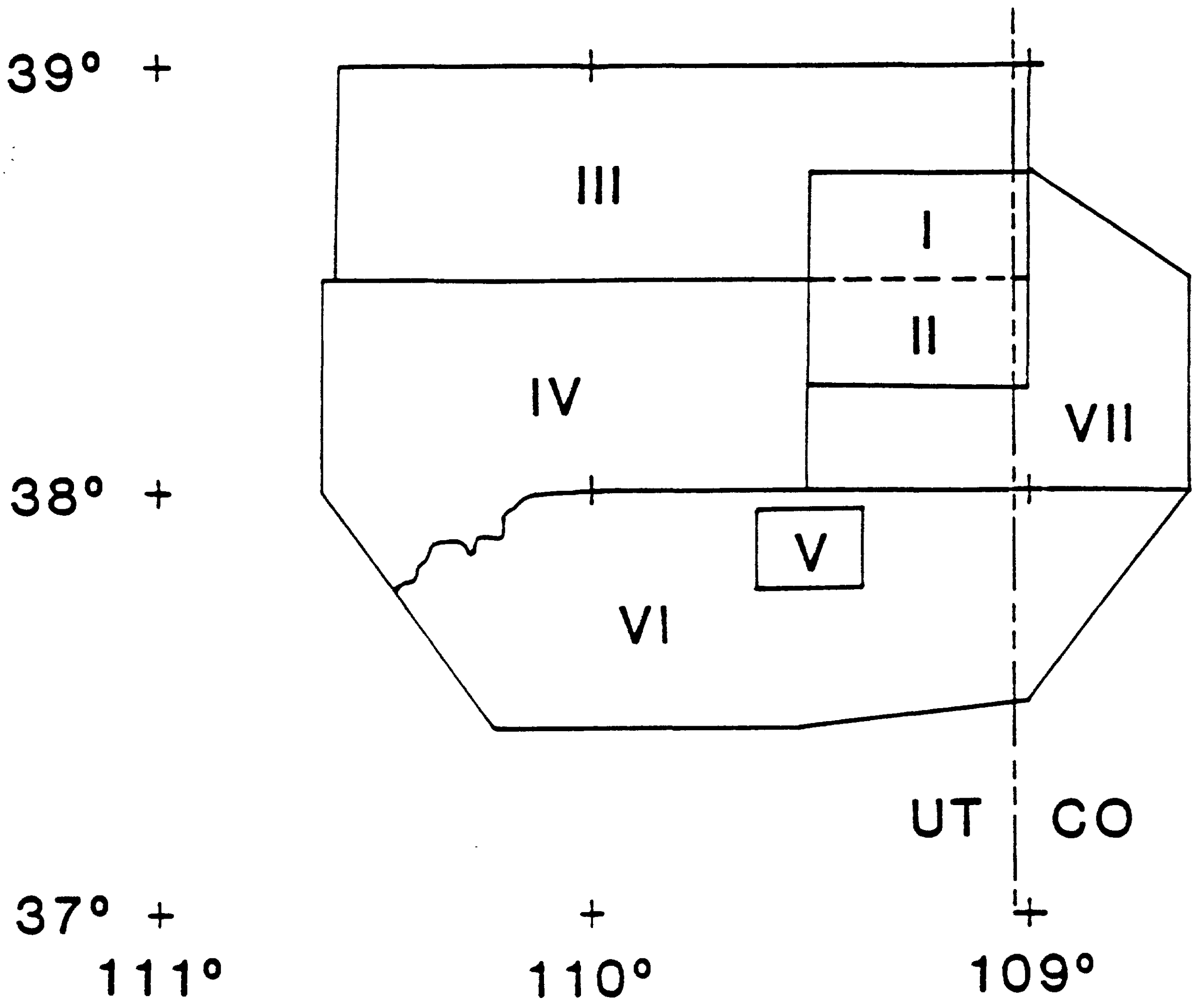
Magnetic Data

Coverage

Aeromagnetic surveys in the study area (fig. 4) were flown by the U.S. Geological Survey between 1953 and 1956 along east-west traverses generally spaced 1.6 km (1 mile) apart. Most of the study area was flown at a barometric elevation of 2591 m (8,500 ft) [constant elevation above sea level]. Flight spacings of 1.6 and 3.2 km (1 and 2 mi) were carried out in the La Sal Mountains (surveys I and II, fig. 4) at a barometric elevation of 3810 m (12,500 ft) and in the Abajo Mountains (survey V) at a barometric elevation of 3505 m (11,500 ft). The only survey flown in a draped mode (constant elevation above terrain) was in the Lisbon Valley-Uravan area (survey VII) where flight elevation was 152 m (500 ft) above ground along traverses spaced 3.2 km (2 mi) apart.

Reduction

Digitization of the published aeromagnetic maps was conducted at the intersections of flight lines and anomaly contours. The residual total magnetic field was obtained by removing the Goddard Space Flight Center (GSFC 12/16) reference field after updating to the epoch that the surveys were flown. The reference field represents the field generated by the Earth's core



Flight Specifications

	Line Spacing	Elevation
I	1 & 2 mi	12,500 ft asl (above sea level)
II	1 & 2 mi	12,500 ft asl
III	1 mi	8,500 ft asl
IV	1 mi	8,500 ft asl
V	1 & 2 mi	11,500 ft asl
VI	1 mi	8,500 ft asl
VII	2 mi	500 ft, above ground

figure 4.- index map of aeromagnetic coverage

and external sources; the residual field is assumed to reflect magnetization inhomogeneities originating within the Earth's crust.

For each individual survey, an elevation of 3810 m (12,500 ft) above sea level was selected as the datum level. Each survey flown at a barometric elevation, except that over the La Sal Mountains, was analytically continued upward to this level; the Lisbon Valley-Uravan survey flown in a draped mode was undraped using a technique developed by Lindrith Cordell (USGS, oral communication, 1982) and upward continued to the selected datum level. Before merging the resulting data sets, magnetic field values of each survey were adjusted by a constant amount, so that they were compatible with those of adjacent surveys. The data sets were then merged using one-dimensional splining techniques described by Bhattacharyya and others (1979).

A 0.75 km grid of values, using a minimum curvature method (Webring, 1981), was created and then converted to a Universal Transverse Mercator (UTM) projected grid with a central meridian of 111°W. The resulting aeromagnetic anomaly map shown in plate 2 is considered as being generated from a set of compatible data and is adequate for studying regional tectonic features.

Accuracy

Aircraft positional errors are assumed small in the Gibson Dome area due to the availability of suitable topographic maps at the time of the survey. Aircraft position over the Lisbon Valley-Uravan area, La Sal Mountains, and Abajo Mountains (surveys I, II, V and VII; fig. 4) was however less accurately determined as topographic maps were unavailable and semicontrolled photomosaics were therefore used. Positional errors are thought to be an unimportant factor considering the map scale (1:250,000) employed in this report.

Aeromagnetic data in the vicinity of Gibson Dome (Joesting and others, 1966) were collected along flight traverses spaced 1.6 km apart and at a barometric elevation of 2591 m [8500 ft] (fig. 4). In future detailed quantitative analyses of these data, the minimum width of magnetic sources that can be detected and interpreted with certainty, is highly dependent on the flight-line spacing. Let us assume that the mean depth of the sources is 3.2 km, the approximate depth to Precambrian basement beneath the flight elevation near Gibson Dome. Utilizing the intimate relationship between flight-line spacing, source depth, and source width, reliable three-dimensional modeling results can be derived for sources having widths greater than about 0.5 km. Two-dimensional sources of smaller widths can be, however, detected and quantitatively interpreted along the flight-line direction where continuous data readings were made. From the above considerations, the aeromagnetic data appears to be suitable for future quantitative interpretations. Nevertheless, higher quality assurance can be maintained if a new aeromagnetic survey flown at a finer flight-line spacing (0.5 km) and in a draped mode (152 m above ground), was conducted within a small region encompassing Gibson Dome. The purposes of this survey are to insure the quality of data collected from previous surveys and to improve on the resolution in interpretational models.

Filtered Data

Filtered gravity anomaly and magnetic anomaly maps were generated to aid in properly locating major geophysical trends, corresponding to faults, folds, and lithologic boundaries. The filters performed the following descriptive operations: (1) separation of gravity sources by wavelength filtering, (2) horizontal derivative analyses to accentuate structural and lithologic boundaries, and (3) trend analyses of the aeromagnetic data to enhance northwest and northeast trending features.

In figure 5, 6, and 7, colored-anomaly maps of the gravity field, magnetic field, and terrain are given so that comparisons can be made with the filtered-anomaly maps. The maps were generated using an Applicon Color plotter.

Regional-residual gravity maps

A gravity-anomaly map exhibits the effects of geological bodies of distinctive density, which may have varying shapes, dimensions, and burial depths. In any region the gravity field is usually caused by the superposition of the overlapping gravitational effects of many bodies whose individual anomalies may be difficult to separate. The terms "residual" and "regional" are arbitrary with respect to scale but are used to make a distinction between anomalies arising from local, near-surface masses and those arising from larger and usually deeper features, respectively. There are many methods for preparing regional and residual maps (Grant, 1972). For our study we chose a general wavelength (or frequency) filtering method to obtain a separation of long wavelength anomalies (regional), that are typically associated with deep-crustal or subcrustal features, from short wavelength anomalies (residual) that are associated with shallow features. We are aware, however, that the separation is not complete and that in particular, some long wavelength anomalies can be caused by broad shallow features. The short wavelengths on the residual maps bring out and emphasize small features, but in some cases the anomaly amplitudes may be distorted by the removal of the long wavelengths.

The gridded data were transformed to the frequency domain by fast Fourier transform and then were low-pass filtered. The low-pass filter was a simple rectangular window, modified so that the gain drops from one to zero along a ramp centered at the cut-off wavelength. The ramp was located between 75 and 50 km: the cutoff wavelength was taken to be 62.5 km. The regional (low-pass) field (fig. 8) was calculated by taking the inverse Fourier transform of the product of the low-pass filter and the Fourier transformed Bouguer gravity field. The residual field (fig. 9) was calculated by subtracting the computed regional field from the unfiltered gravity field.

The validity of the wavelength filtering process in calculating regional-residual gravity fields is dependent on the assumption that the cut-off wavelength of the filter and maximum depth of source are related. Preliminary analyses suggest that the maximum source depth is roughly equal to the cut-off wavelength divided by a factor ranging from 6 to 12, depending on the geometry of the source. Thus, the residual gravity map composed of wavelengths of 62.5 km and less, exhibits anomalies which probably are associated with sources that lie above a depth of between 5 and 10 km; the effects of broad shallow

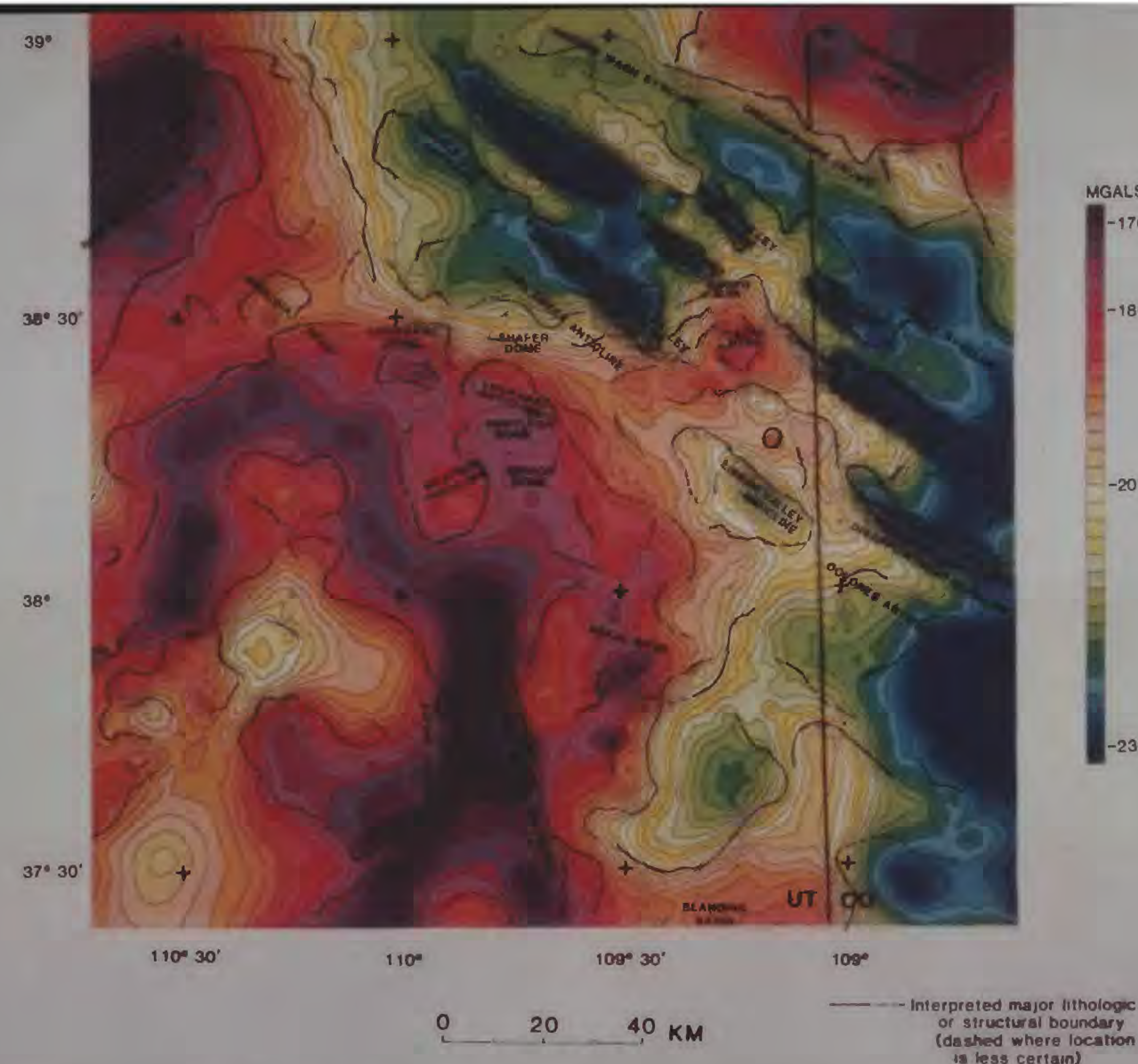


figure 5.- BOUGUER GRAVITY

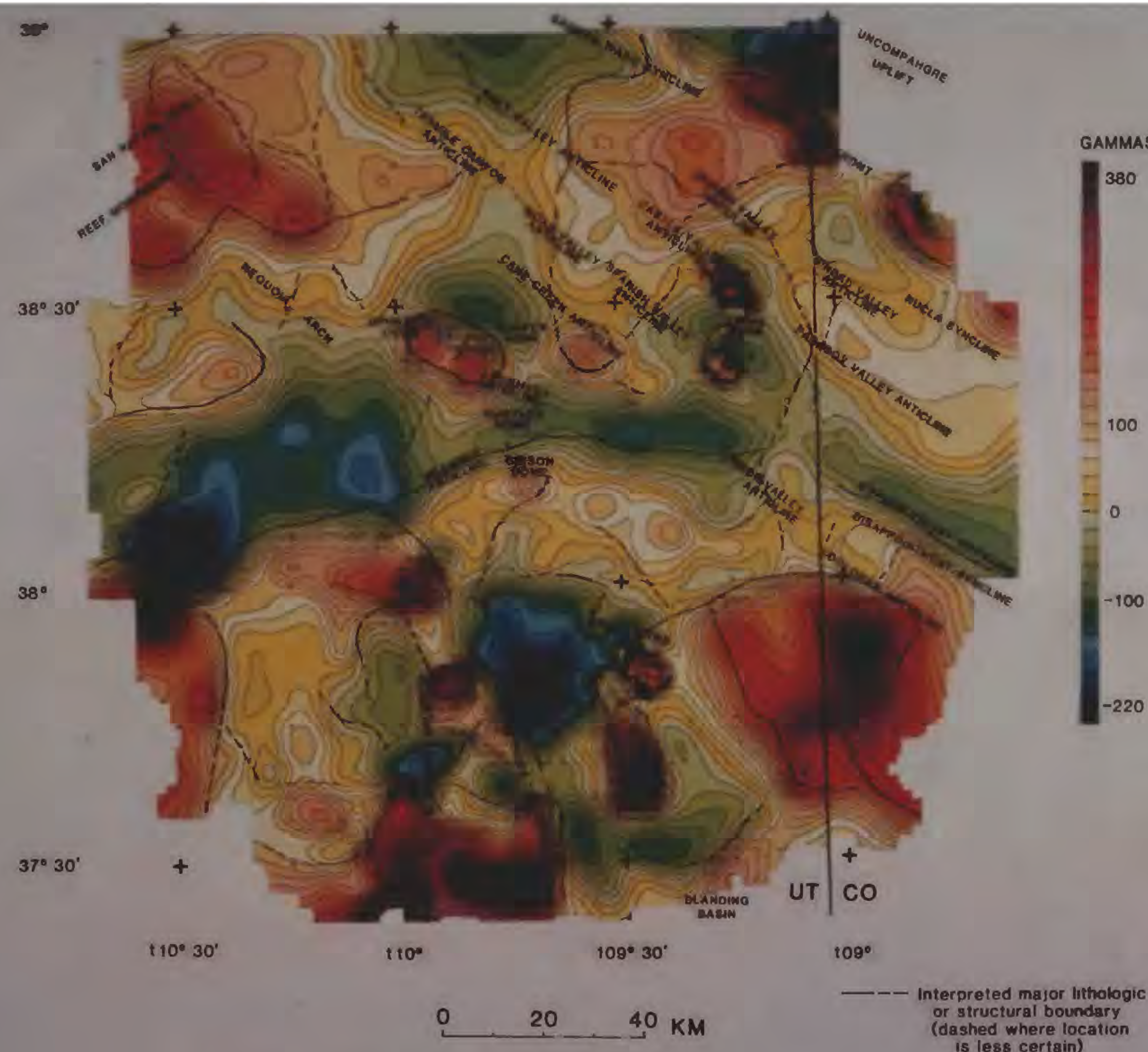


figure 6.- RESIDUAL TOTAL MAGNETIC INTENSITY

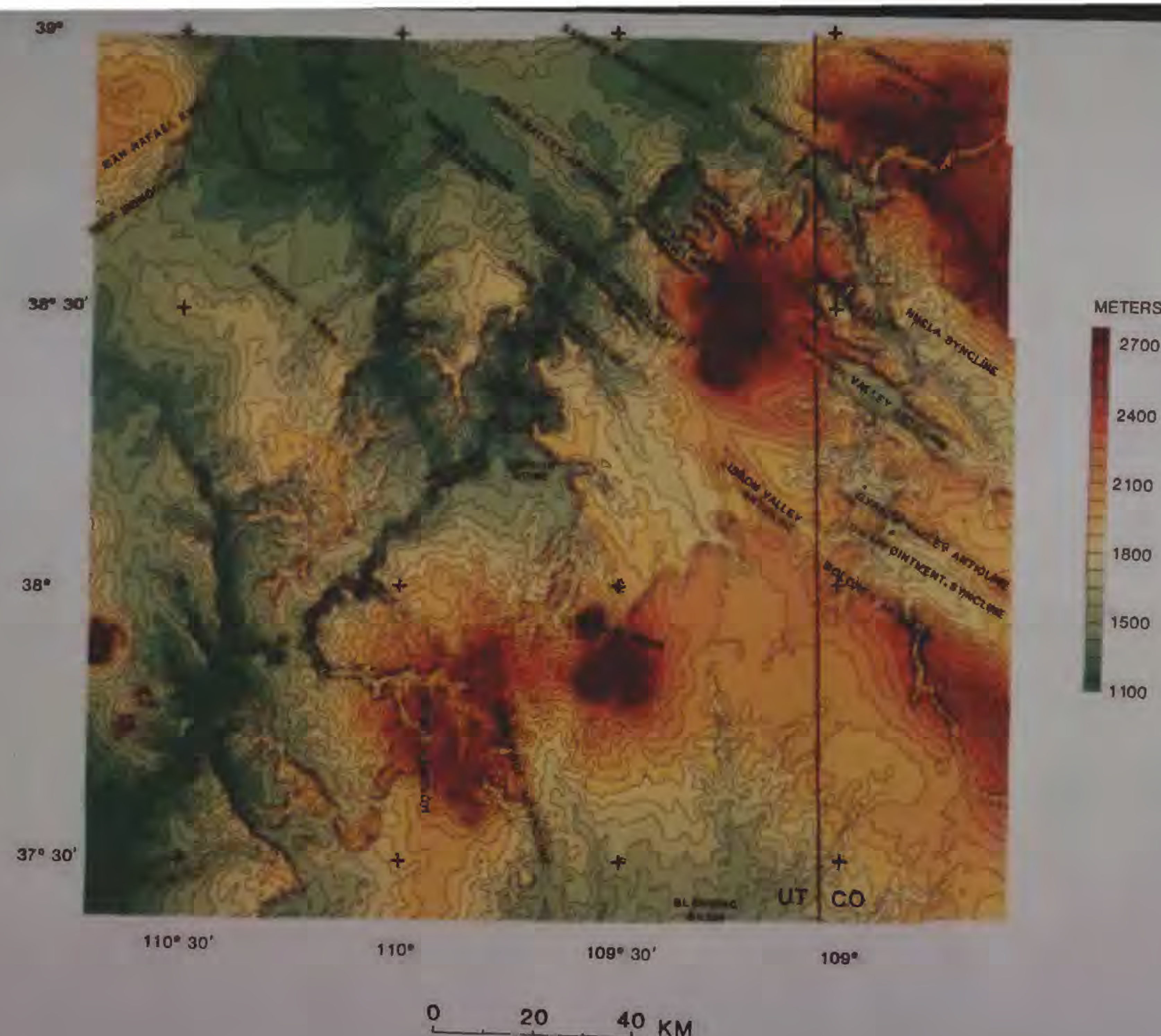


figure 7.- TERRAIN ELEVATION WITH RESPECT TO SEA LEVEL

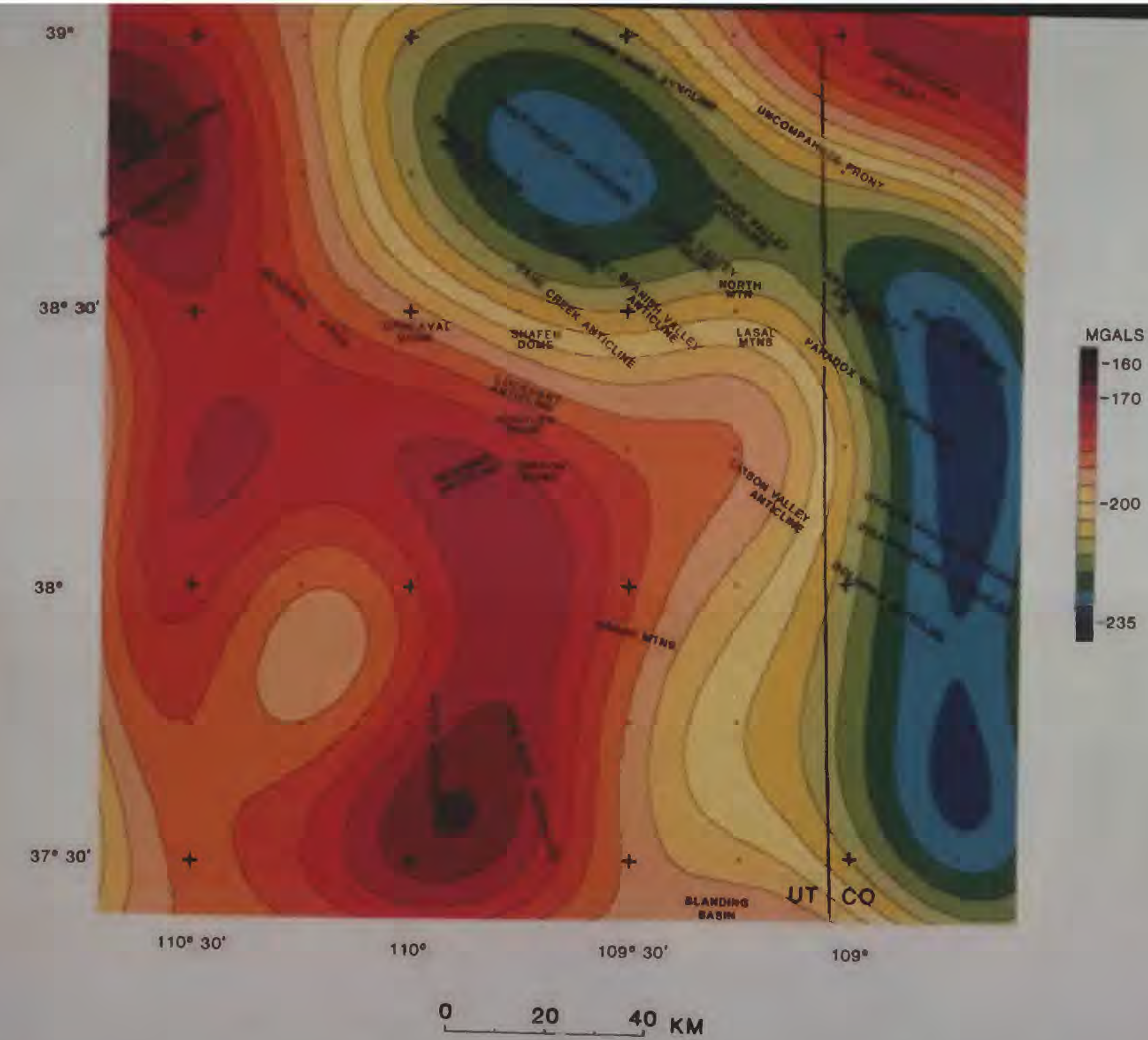


figure 8.- REGIONAL GRAVITY:WAVELENGTHS GREATER THAN 62.5 KM

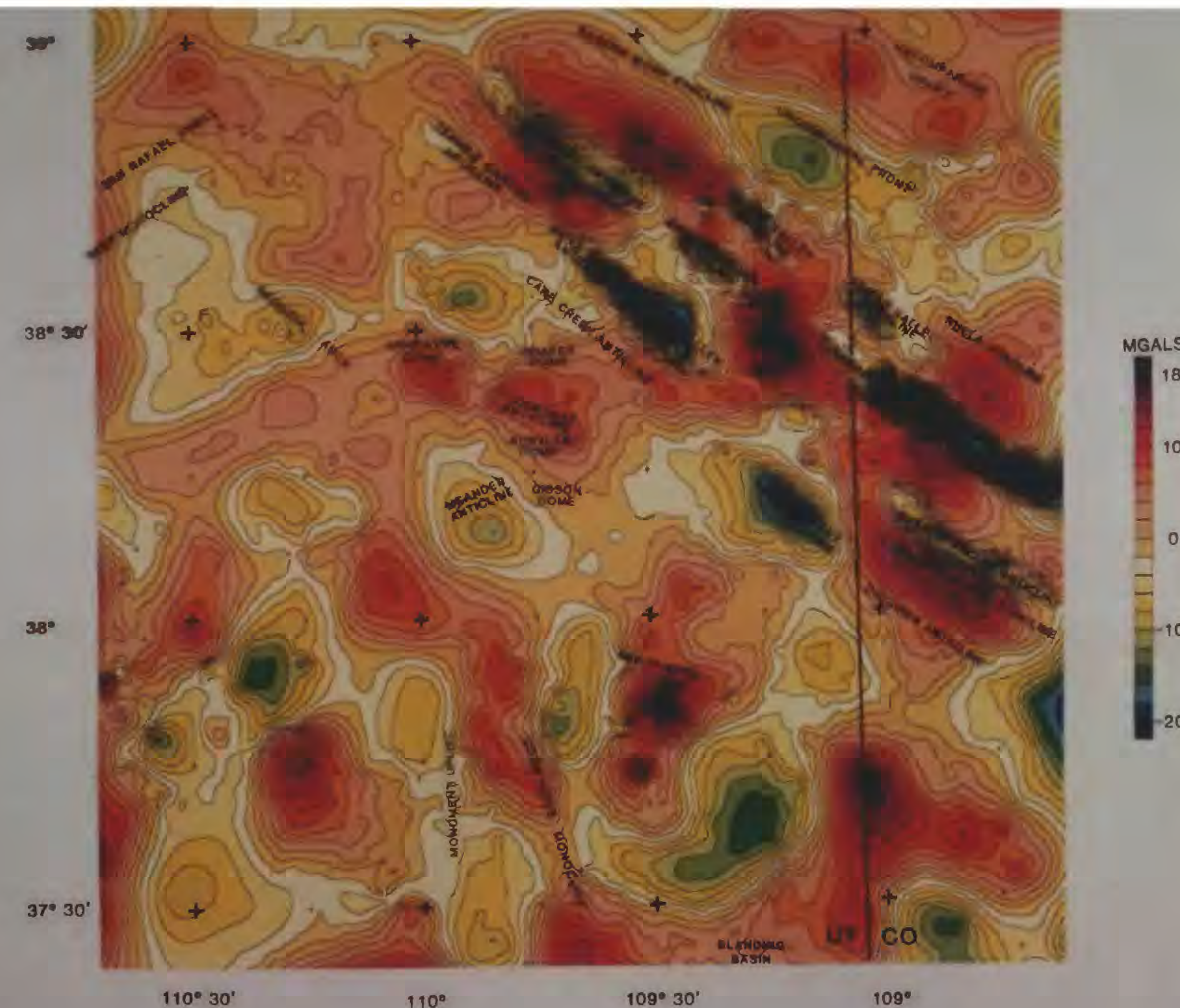


figure 9.- RESIDUAL GRAVITY:WAVELENGTHS LESS THAN 62.5 KM

sources such as low-density sedimentary strata, however, are not present on this map. Conversely the complementary 62.5 km wavelength low-pass map represents the effects of deeper sources, such as the shape of the crust-mantle boundary and anomalous masses in the mantle and middle and lower crust, and presumably those of any broad shallow masses that may be present.

Regional gravity highs (fig. 8) coincide with the Uncompahgre Uplift, Monument Uplift, and San Rafael Swell where dense Precambrian rocks occur at shallower depths. The gravity low located southwest of the Uncompahgre Front reflects greater sedimentary accumulation in the deepest part of Paradox Basin (Case and Joesting, 1972a). Precambrian rocks of lower density may produce the gravity low in the southwest corner of the map. On the other hand, the residual gravity map (fig. 9) exhibits anomalies generally associated with smaller scale features lying at shallower depths within the tectonic divisions defined on the regional gravity map. These residual anomalies and their associated sources are discussed later in more detail.

Horizontal-gradient anomaly maps

Major lithologic and structural boundaries within Precambrian basement and the sedimentary column above basement, readily produce identifiable gradients on the gravity anomaly map. Because these boundaries are often difficult to accurately locate, especially those underlying broad gradients, a horizontal gravity gradient map (fig. 10) was generated. Maximum gradient magnitudes occur over density inhomogenieties. Lines drawn along ridges formed by enclosed high gradient magnitudes presumably correspond to properly located structural trends or contacts (Cordell, 1979). Shown in figure 10 are the interpreted gravity trends, which are also shown on the unfiltered gravity anomaly map in figure 5. Due to the possibility of significant elevation and terrain correction errors, only the larger gradient magnitudes were used to delineate contacts. The magnitude of the horizontal gradient of the Bouguer anomaly field was calculated employing the basic equation:

$$|\text{gradient}| = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2}$$

where x is the latitudinal coordinate, y is the longitudinal coordinate, and g is the gravity value.

This technique can also be applied to the magnetic data but first a pseudo-gravity transformation must be carried out. Gravity and magnetic anomalies caused by a common source of magnetization and density contrast are related to each other by Poisson's equation:

$$\frac{m}{J} = \frac{1}{G\rho}\,\frac{\partial g}{\partial z}$$

where g = gravity field,
m = magnetic field reduced to the North pole,
J = magnetization contrast,
ρ = density contrast,
G = Universal Gravitational Constant,
and z = vertical coordinate.

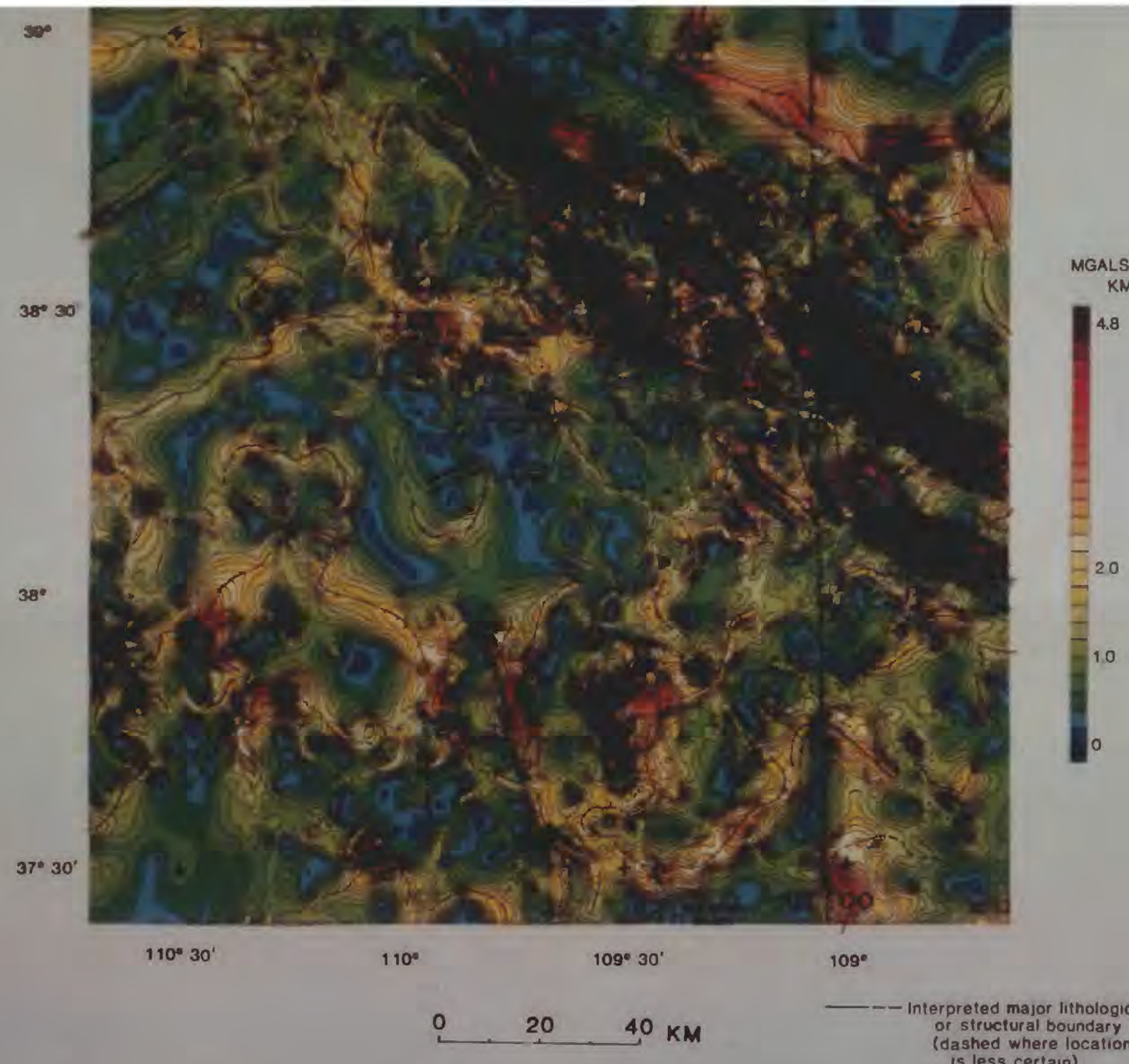


figure 10.- HORIZONTAL GRADIENT OF BOUGUER GRAVITY

The pseudo-gravity field calculated from the above equation was used to produce the horizontal gradient map shown in figure 11. For this calculation, it was assumed that the magnetization vector contains only an induced component with an inclination of 64.8°N and a declination of 13.6°W and that the ratio of density contrast and magnetization contrast is 0.001 g/cm^3/gammas. The interpreted magnetic trends are shown in figure 11 and on the unfiltered magnetic anomaly map in figure 6.

In a comparison of figure 10 and figure 11, the quantity of interpreted trends are noticeably less on the gradient map derived from the pseudo-gravity field or the magnetic field. As will be discussed later, there are several density discontinuities within the Phanerozoic sediments (such as salt beds) that have no effect on the magnetic field. These sedimentary mass inhomogenieties are, therefore, expressed on the horizontal gravity gradient map but not on the pseudo-gravity gradient map. Both the interpreted magnetic lineaments and gravity lineaments are shown in plate 3.

Northwest and northeast trend maps

Trend analysis of the geophysical maps involves passing anomalies striking between two specified directions and rejecting all other anomaly trends. In figure 12, magnetic features trending between north and west are shown; the complementary northeast trend map is shown in figure 13. Trend maps are used only in a qualitative way, and care must be taken in interpreting these maps. Because anomalies become elongated in the selected filtering direction, caution must be exercised in delineating long continuous trends. Only features indicated on the unfiltered magnetic map can be interpreted on trend maps. Although this restriction is stringent, trend maps are often useful in enhancing linear features that are real but not easily identifiable on the unfiltered magnetic anomaly map. Trend maps are also useful for estimating anomaly errors associated with flight-line direction.

Description of Major Geophysical Features

Qualitative interpretations of the regional magnetic, gravity, and related filtered anomaly maps supply information on Precambrian lithologic and structural boundaries and on lateral compositional variations of the sedimentary column above basement. Phanerozoic sediments are assumed to be essentially nonmagnetic and produce little or no effect in the magnetic field. Magnetic basement is interpreted as Precambrian crystalline rocks unless intruded by igneous rocks of younger age. Precambrian basement is characterized by complex lithologies (table 1) resulting in variable densities and magnetic properties (Case, 1966). Reported average densities and susceptibilities of Precambrian rock types are as follows: gneisses - 2.7 g/cm^3, 0.134×10^{-3} emu/cm^3; quartz monzonite - 2.71 g/cm^3, 1.22×10^{-3} emu/cm^3; metagabbro and metadiorite - 2.88 g/cm^3, 0.16×10^{-3} emu/cm^3 (possibly higher because measurements were made on weathered specimens). The undulating surface of Precambrian basement rises toward the crests of the Uncompahgre Uplift, Monument Uplift, and San Rafael Swell and descends deeply into the deep part of Paradox Basin (inset, plate 3). Many of the magnetic and gravity anomalies can be related to relief on the Precambrian surface and to magnetization and density contrasts within Precambrian basement.

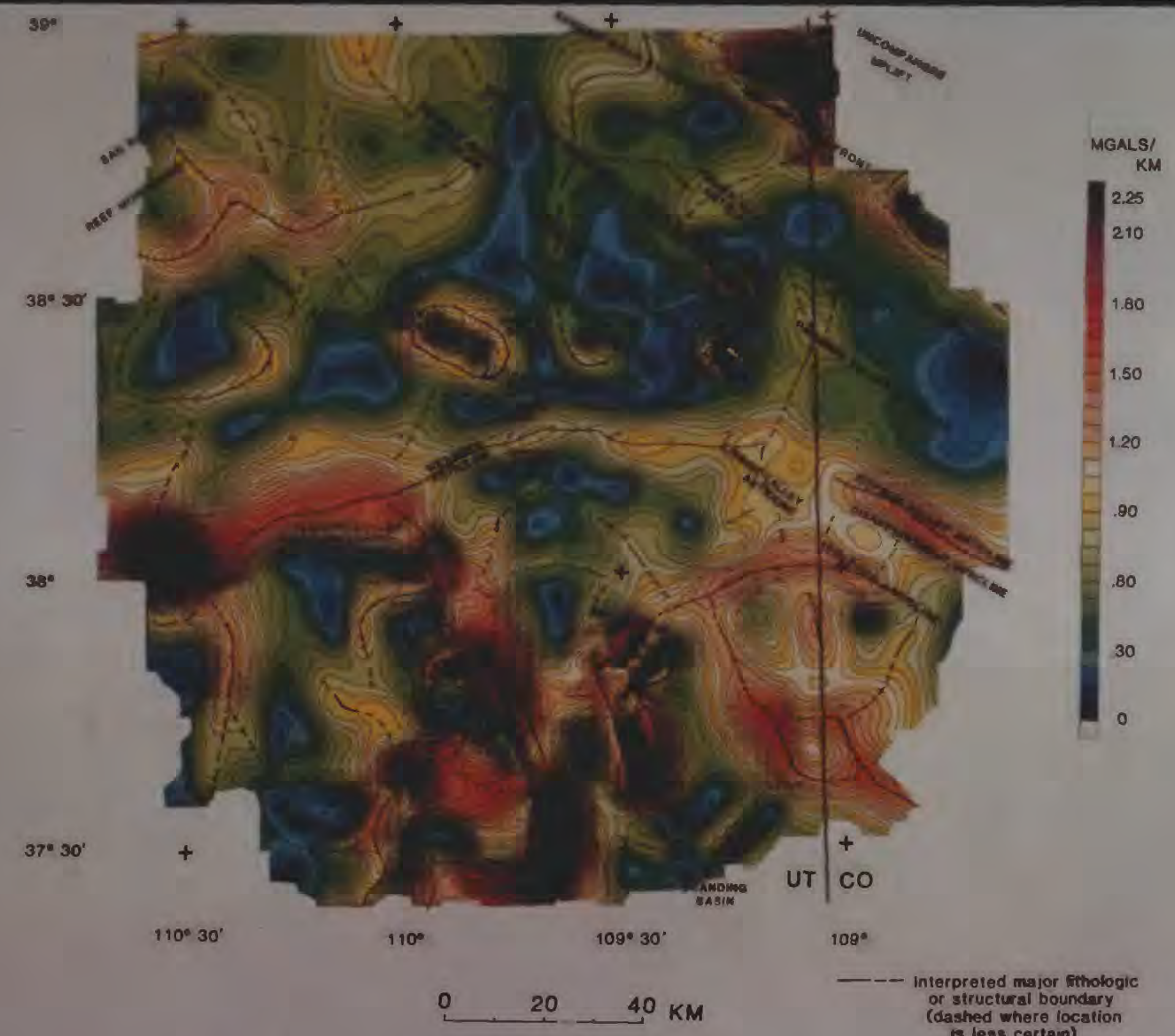


figure 11.- HORIZONTAL GRADIENT OF PSEUDO-GRAVITY

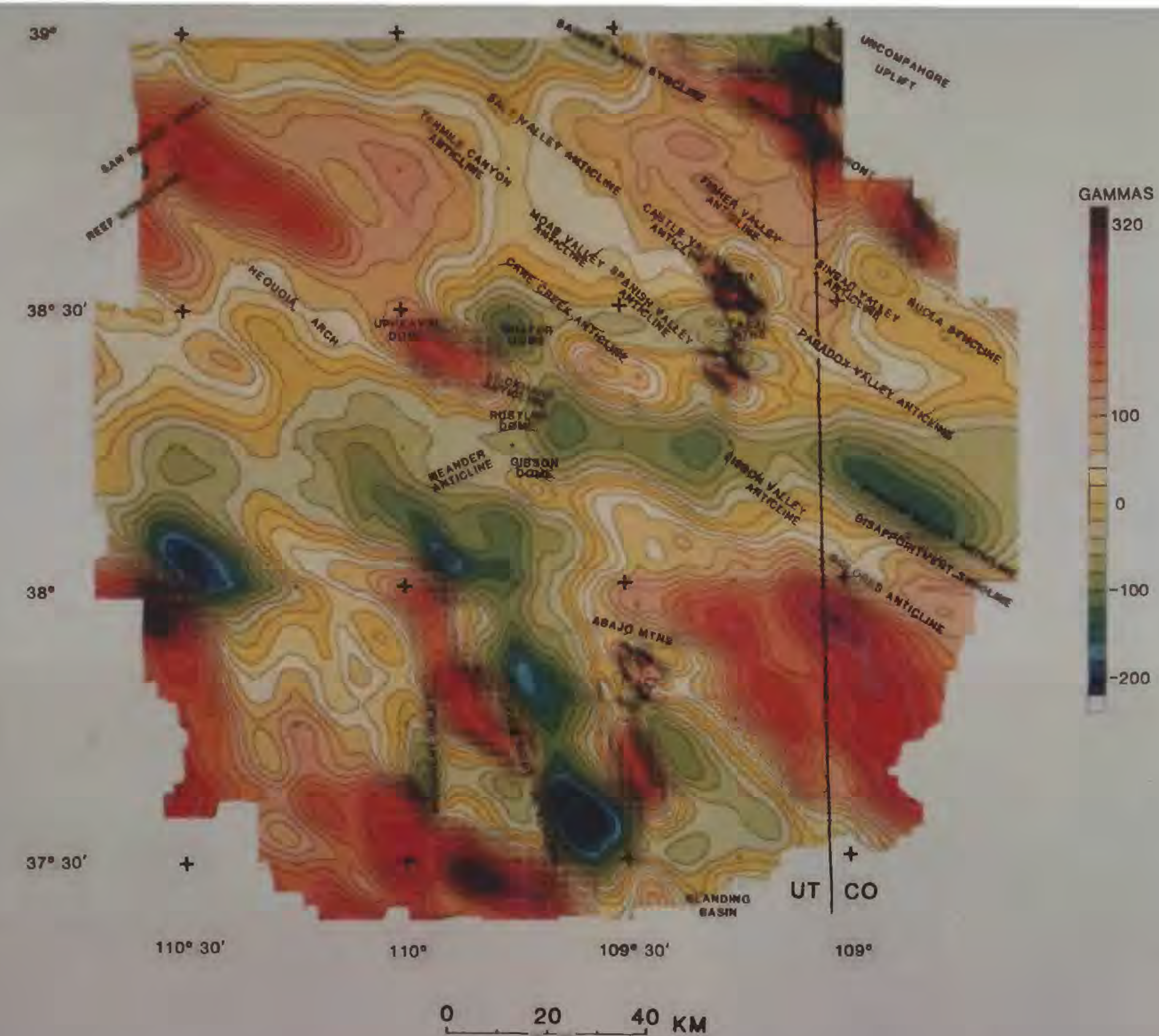


figure 12.- NORTHWEST MAGNETIC-ANOMALY TRENDS

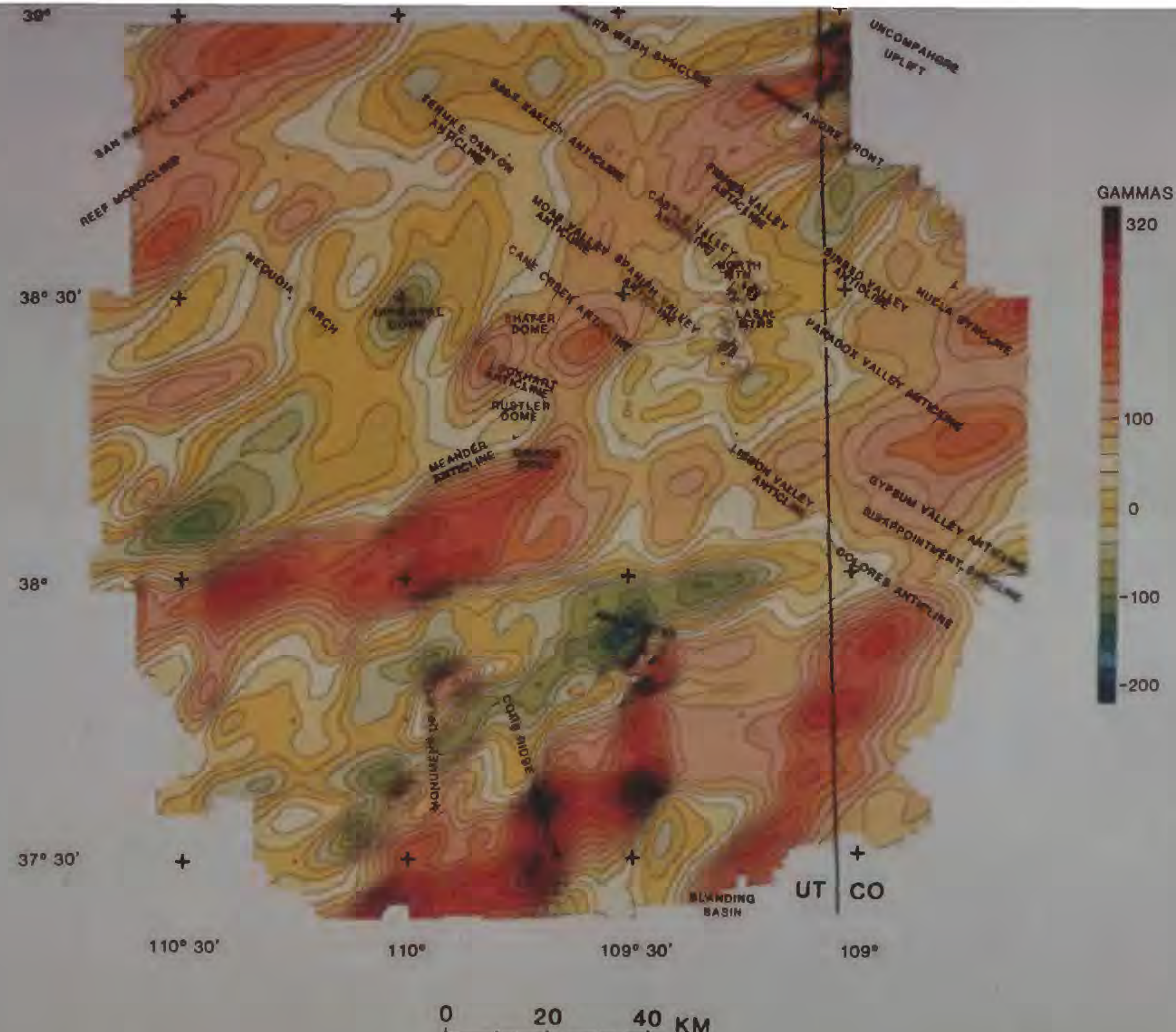


figure 13.- NORTHEAST MAGNETIC-ANOMALY TRENDS

System	Stratigraphic unit	Thickness (feet)	Lithology	Estimated density (g/cm³)
Quaternary		0–500?	Alluvial sand, silt, and gravel, talus, and windblown deposits. Local glacial deposits.	2.2–2.4
Tertiary	Chuska Sandstone Green River Formation Wasatch Formation	0–2,000?	Sandstone, tuff, siltstone, and conglomerate.	2.3–2.4
Cretaceous	Mesaverde Group Mancos Shale	2,500?	Shale and siltstone.	2.3–2.45
	Dakota Sandstone Burro Canyon Formation	200?	Sandstone and conglomerate.	
Jurassic	Morrison Formation	540–850	Shale, siltstone, sandstone, and conglomeratic sandstone.	2.3–2.5
	San Rafael Group: Summerville Formation Curtis Formation Entrada Sandstone Carmel Formation	400–750	Sandstone and siltstone.	
Jurassic, Triassic(?), and Triassic	Glen Canyon Group: Navajo Sandstone Kayenta Formation Wingate Sandstone	550–1,100	Sandstone and siltstone.	
Triassic	Chinle Formation Moenkopi Formation	0–1,600	Shale, siltstone, sandstone, and conglomerate.	
Permian	Cutler Formation	0–8,000	Arkosic sandstone, quartzose sandstone, and shale.	2.58–2.65
Permian(?) and Pennsylvanian	Rico Formation	0–575	Limestone, shale, and arkosic sandstone.	
Pennsylvanian	Hermosa Formation: Upper member	0–2,500	Limestone, shale, and sandstone.	
	Hermosa Formation: Paradox Member	0–4,000+	Salt, gypsum, black shale, and limestone.	2.2–2.3?
	Hermosa Formation: Lower member	0–400	Limestone and shale.	2.6–2.7
	Molas Formation	0–150	Shale, sandstone, and limestone.	
Mississippian, Devonian, and Cambrian		0–4,200	Limestone, shale, dolomite, and sandstone.	
Precambrian			Quartz monzonite, granite, schist, gneiss, metagabbro, amphibolite, quartzite, and argillite.	2.6–3.2?

table 1.-- Generalized stratigraphy of the central Colorado plateau (from Case and Joesting, 1972a)

Major compositional variations within the Phanerozoic sedimentary sequence are expressed in the gravity field. From the listed densities in table 1, significant sedimentary density discontinuities occur at the top of the Cutler Formation, Paradox Member of the Hermosa Formation, and Lower Member of the Hermosa Formation. Major structural features on the surface of these discontinuities are reflected in the gravity field.

The compiled anomaly maps reveal features of varying intensities and wavelengths. For example, short-wavelength, high-amplitude anomalies are coincident with the laccolithic La Sal and Abajo Mountains. Broad regional gravity highs over the Uncompahgre Uplift, Monument Uplift, and the San Rafael Swell express shallower depths to Precambrian basement. Over these upwarps magnetic anomalies are generally characterized by steep gradients and large amplitudes. In the region between the Monument Uplift and the Uncompahgre Uplift, thick accumulations of Phanerozoic sediments within the deepest part of Paradox Basin (inset, plate 3) result in a broad gravity low and longer-wavelength magnetic anomalies. Superimposed on this regional gravity low are shorter wavelength anomalies primarily reflecting mass inhomogeneities within the sedimentary column above basement. For example, the prominent linear lows coincide with the northwest-trending, low-density salt anticlines. The diverse anomaly patterns indicated on the anomaly maps suggest that Paradox Basin underwent a long and complex history, resulting in the formation of major geologic features with complex lithologies and structures.

Many of the magnetic and gravity features (plate 3) discussed below trend northwest or northeast and coincide with patterns of lineamentation defined from remote sensing imageries (Friedman and Simpson, 1978; Woodward-Clyde, 1982a). The correlation of lineament trends from these two geophysical methods suggests Precambrian basement control in the development of many of the surface features (faults, fractures, and joints) throughout Paradox Basin (Friedman and others, 1983).

The following discussions of geophysical features in Paradox Basin are primarily a summary of the work conducted by Byerly and Joesting (1959), Case (1966), Case and Joesting (1961, 1972a), Case and others (1963), Joesting and Byerly (1956, 1958), Joesting and Case (1962), and Joesting and others (1966). Because a generalized treatment of their interpretations is given here, the reader is referred to these publications for more detailed descriptions, rock associations and discussions. However, some new interpretative results are given in the present study, and emphasis of the discussions is placed on structures and lithologies in the Gibson Dome area.

Major salt anticline systems

The dominating gravity features in Paradox Basin are large-amplitude lows in the northeastern part of the study area that trend northwest parallel to the Uncompahgre Front. They express underlying salt anticlines where low-density (2.25 g/cm^3) salt-bearing cores range in thickness from about 760 to 4300 m (Hite and Lohman, 1973; Case and Joesting, 1972a). On the basis of geographic and structural information, Hite and Lohman divided the salt anticlines into five major systems: (1) Lisbon Valley-Dolores Valley; (2) Moab Valley-Spanish Valley-Pine Ridge; (3) Gypsum Valley; (4) Castle Valley-Paradox Valley; and (5) Salt Valley-Cache Valley-Fisher Valley-Sinbad Valley. Although northwest-trending structures of Precambrian age controlled salt anticline locations, the anticlines probably achieved most of their growth in Permian time (Cater, 1972).

Structural lows possibly formed by faulting allowed migration of the Paradox strata (table 1) from flanking synclinal areas to some of the salt anticlines (Hite and Lohman, 1973). From gravity modeling of the steep gradient bordering the southwest flank of the Paradox Valley anticline, Joesting and Case (1960) interpreted about 1500 m of offset along a steeply dipping normal fault (plate 3). This agreed with subsequent drill-hole data of 1700 m of offset (Baars, 1966). Structural closures against the Lisbon fault, lying along the northeast flank of the Lisbon anticline, is about 760 m (Hite and Lohman, 1973). Byerly, Case, and Joesting believe the steep gravity gradients bordering many of the other salt anticlines suggest displacement in pre-salt basement.

In figures 5 and 9, prominent gravity highs flank the Salt Valley, Paradox Valley, and Gypsum Valley anticlines; smaller-amplitude highs border the Fisher Valley, Castle Valley, and Sinbad Valley anticlines. A plausible explanation for these highs is that the anticlines developed on structural highs on the pre-salt or Precambrian surface with horizontal dimensions greater than that of the anticlines. These structural highs apparently correspond to northwest-trending folds or horsts along which axial or border faulting (reverse or high-angle thrusting) may have occurred. The implied deformation on pre-salt surfaces probably resulted in local structural lows which allowed migration of salt beds to form the anticlines.

The salt anticlines produce no or little effect in the magnetic field. Magnetic highs along the southwest flank of Gypsum Valley were interpreted by Joesting and Byerly (1958) as reflecting a Precambrian basement ridge or structural high. The magnetic low that roughly coincides with the Gypsum Valley anticline may express a greater depth of burial of Precambrian rocks.

Uncompahgre Uplift and surrounding region

Gravity and magnetic highs in the northeastern corner of the study area overlie the Uncompahgre Uplift, a huge monoclinal upwarp along which outcrops of Precambrian rocks are present. Approximately 6400 m of structural relief occurs on the top of Precambrian basement from the deep part of Paradox Basin across the Uncompahgre Front. The Uncompahgre Front represents a steeply dipping monocline that was an active tectonic boundary during late Paleozoic and Laramide time (Case, 1966; Elston and others, 1962). On the Uncompahgre Plateau, basement is characterized by highly deformed metamorphic and igneous rocks.

Case and Joesting (1972a) correlated many magnetic and gravity anomalies with well-exposed Precambrian rocks. Positive magnetic highs located immediately northeast of the Uncompahgre Front reflect a batholith of biotite quartz monzonite. Weakly magnetized metamorphic rocks are present northeast of the batholith. The Little Dolores River metagabbro pluton (latitude 38°57′N, longitude 109°W) coincides with a prominent gravity and magnetic high. Case and Joesting (1972a) indicated that granitic rocks on the southwest flank of the uplift are less dense than the gneisses and metagabbros on the uplift.

Concealed quartz monzonite may extend westward beyond the Uncompahgre Front into the deep part of Paradox Basin (Case and Joesting, 1972a). A broad magnetic high north of the La Sal Mountains probably reflects these highly magnetic batholithic rocks. Case and Joesting (1972a) interpret a basement fault zone that coincides with the steep gradient on the south flank of this magnetic high (plate 3).

San Rafael Swell and surrounding region

The San Rafael Swell is a northeast-trending monoclinal uplift in the northwestern part of the study area. Approximately 600 to 1500 m of relief is present on the surface of Precambrian basement from the foot of the Reef Monocline to the crest of the uplift. Regional magnetic and gravity highs reflect this structural high. The zone of magnetic highs trending southeast from the San Rafael Swell (figs. 6 and 12) and the high south of the Reef Monocline (latitude 38°35′N, longitude 110°33′W) may delineate mafic intrusions, possibly of dioritic or gabbroic composition (Case and Joesting, 1972a). Moderate-amplitude gravity anomalies (figs. 5 and 9) are coincident with these magnetic highs. An east-west trending magnetic and gravity high southwest of Tenmile Canyon anticline may also reflect intermediate to mafic rocks. On the other hand, there is no identifiable gravity high in the region of the magnetic high south of the San Rafael Swell (latitude 38°22′N, longitude 110°23′W). The magnetic high is apparently associated with moderately to highly magnetic Precambrian rocks with densities similar to those of the surrounding host rock, such as quartz monzonite.

Monument Uplift

The Monument Uplift is a broad north-trending asymmetrical fold bordered on the east by the Comb Ridge Monocline. Gibson Dome lies on the northeast flank of the Monument Uplift. The axis of the upwarp lies generally within 24 km of the Comb Ridge monocline, but the western flank descends gently toward the Henry Mountains located west of the study area. Over this structural high intense anomalies with steep gradients generally characterize the gravity and magnetic terranes which are interpreted as having intrabasement origins (Case and Joesting, 1972a). The north and north-northwest trending zone of gravity and magnetic highs (figs. 5, 6, 9, and 12) roughly follow the structurally highest parts of the uplift to latitude 38°N and may reflect Precambrian mafic rocks. Gravity highs (fig. 9) continue northward to an area west of Upheaval Dome and then southwestward to latitude 38°15′N. These gravity highs occur within a broad magnetic low trending east-northeast. Case and Joesting (1972a) interpreted the gravity highs as reflecting dense Precambrian rocks, similar to those on the Uncompahgre Plateau where gneissic granodiorite and amphibolites are dense but almost nonmagnetic.

The pronounced magnetic high at latitude 37°55′N and longitude 110°33′W coincides with a gravity high of moderate amplitude. The source may be a highly magnetic intrusion lying within Precambrian basement but of unknown age (Case and Joesting, 1972a). Farther south and southeast, several gravity and magnetic lows indicate local areas underlain by Precambrian rocks of low density and weak magnetization (e.g. granite or sedimentary rocks). The prominent gravity high at latitude 37°45′N and longitude 110°15′W is associated with a small amplitude magnetic high and may reflect amphibolites or gneissic granodiorite like those delineated farther north near Upheaval Dome.

Blanding Basin and surrounding region

Heterogeneous gravity and magnetic patterns related to Precambrian lithologic variations are also present in this area as discussed by Case and Joesting (1961, 1972a). They interpret the arcuate zone of magnetic and gravity highs extending north-northeast from the deep part of Blanding Basin to latitude 37°45′N as delineating moderately dense and magnetic rocks (possibly dioritic). Basement of similar composition may produce the zone of magnetic and gravity highs trending northwest from the southeast corner of the study area. The broad magnetic and gravity low located between the Abajo Mountains and Blanding Basin may reflect Precambrian granites or a thick quartzite sequence (Case and Joesting, 1972a). Case and Joesting (1972a) suggest that the northeast-trending zone of linear steepened gravity gradient bordering the gravity low on the southeast, represents a deep-seated fault in Precambrian basement (plate 3). The prominent magnetic high southwest of the Dolores anticline occurs only locally with small amplitude gravity highs (fig. 9). Local salt thickening may reduce the amplitude of the gravity field in this region (Case and Joesting, 1972a).

Laccolithic mountains

The high and rugged La Sal and Abajo Mountains lie within the study area. They consist of Tertiary intrusive rocks (mostly syenite, diorite, and monzonite porphory) that form one or more central stocks with associated dikes and sills. Average density and magnetic susceptibility of these rocks are 2.6 g/cm^3 and 1.6×10^{-3} emu/cm^3, respectively (Case and Joesting, 1972a).

Over the La Sal Mountains three high-amplitude, short-wavelength magnetic anomalies coincide with main stocks and laccoliths which form topographic highs. From magnetic anomaly modeling, Case and Joesting (1963) calculated a floored laccolith mass that is 610-910 m thick forming North Mountain and 1220-1520 ft thick forming South Mountain. They suggested that steep northeast and northwest trending gravity gradients near latitude 38°30′N (plate 3) indicate zones of basement weakness that were intimately related to the formation of the north mountain group located near the intersection of the zones. The gravity field over the La Sal Mountains is characterized by a broad high on which several higher-amplitude, short-wavelength anomalies are superimposed.

Over the Abajo Mountains magnetic highs correlate with laccoliths or stocks described by Witkind (plate 1, 1964). Case and Joesting (1972a) suggested that the intersection of basement fractures represented by northeast and northwest trending magnetic gradients (fig. 6, plate 3), has localized intrusions in the Abajo Mountains. Prominent gravity and magnetic highs trending south from the Aabjo Mountains have been interpreted as a dioritic or gabbroic rock mass by Case and Joesting (1972a). The pronounced magnetic and gravity lows west of the Abajo Mountains (figs. 6 and 9) probably delineate low-density and weakly-magnetized Precambrian granites or sedimentary rocks.

Gibson Dome area

The above discussions relating gravity and magnetic anomaly patterns to rock types and structures indicate that the study area is characterized by a heterogeneous Precambrian basement ranging in composition from gabbroic to granitic, by an undulating Precambrian surface rising toward three uplifts and descending beneath two basins, by basement fault blocks primarily trending northeast and northwest, and by salt anticlines that developed on pre-salt structural lows (possibly fault bordered). These observations aid in understanding the magnetic and gravity terranes and their correspondence to upper crustal structures and lithologies in the Gibson Dome area, the area of interest. Gibson Dome is a gentle west-northwest trending fold (plate 3), formed from the migration of salt into a warped or faulted structural low. Structural closures on this fold was estimated by Hite and Lohman (1973) to be 61 m.

The dominent magnetic features in the area are large amplitude, circular highs lying to the northeast and northwest of Lockhart anticline and to the southeast of Gibson Dome. Because these anomalies coincide with moderate-amplitude gravity highs (fig. 9), Case and Joesting (1972a) suggested that they are related to intermediate-mafic intrusions (dioritic or gabbroic) in Precambrian basement. The two magnetic highs northwest of Lockhart anticline are aligned with the zone of magnetic highs extending southeast from the San Rafael Swell. The implied semi-continuous zone of magnetic highs (figs. 5 and 12) extending from the San Rafael Swell to the Lockhart anticline, may reflect a zone of Precambrian(?) mafic intrusions (Case and Joesting, 1972a), emplaced along a deep-seated, northwest-trending fault system or zone of weakness (plate 3). One of the two magnetic anomalies northwest of Lockhart anticline overlies Upheaval Dome, which is thought to be a salt dome. The domal structure may be intimately related to the interpreted intrusion located directly beneath the dome (plate 3).

The magnetic high near the Cane Creek anticline is very similar in character to those near Upheaval Dome. Case and Joesting (1972a) suggested that a northeast-trending fault (plate 3) with left-lateral displacements has offset the associated intrusion by about 14 km from the two interpreted intrusions near Upheaval Dome. The northeast-trending shear zone may form part of the Colorado Mineral Belt that extends across Paradox Basin along a zone approximately 200 km wide (Hite, 1975; Warner, 1978; Tweto, 1980).

The Lockhart anticline is a small fold on which the structural closure is about 30 m (Hite and Lohman, 1973). The Lockhart fault which separates Lockhart anticline from Lockhart Basin (plate 3) has a maximum offset of 73 m down on the southwest. Dissolution of salt occurred within the structurally complex basin and resulted in the collapse of overlying sedimentary layers and in folding and faulting. A gravity high of moderate amplitude coincides with Lockhart Basin and probably reflects, in part, the thinning and absence of low-density evaporites.

The Cane Creek anticline lying northeast of Lockhart Basin has little or no gravity expression, possibly indicating locally little additional accumulation of Paradox evaporites. The anticline terminates near the Trough Springs Canyon fault which appears to be in an en echelon alignment with the Lockhart fault. Field mapping indicates that these faults do not form a continuous fault system (Woodward-Clyde Consultants, 1982b). There is also no indication in the gravity and magnetic fields that a single fault system exists between Cane Creek anticline and Lockhart anticline. Both the Lockhart fault and the Trough Springs Canyon fault parallel and thus may be related to the shear zone northwest of Lockhart anticline interpreted by Case and Joesting (1972a).

The northwestern part of the broad gravity anomaly (fig. 9) over Lockhart anticline is associated with a prominent magnetic high and was interpreted above as delineating a Precambrian(?) mafic intrusion. The southeastern part of the anomaly near Lockhart Basin, however, has no coinciding magnetic high. The gravity high extends southward from Lockhart Basin to Gibson Dome across a region of essentially horizontally bedded strata (Woodward-Clyde Consultants, 1982b). A mass excess in the Phanerozoic sediments does not, therefore, appear to be the cause of the gravity high. Precambrian rocks similar to the gneissic granodiorite and amphibolites on the Uncompaghre Upwarp, which are dense but nonmagnetic, may underlie the region from Lockhart anticline to Gibson Dome. New information from the analysis of additional gravity data may help in delineating the source of the north-south trending zone of gravity highs.

The long-wavelength gravity low west of Gibson Dome may reflect low-density Precambrian rocks or local depositional thickening of the Paradox evaporites (Case and Joesting, 1972a). A zone of magnetic highs coincident with the gravity low suggests that the anomalies are produced by Precambrian rocks (granites?) of low density and moderate magnetization. The Meander anticline, a salt anticline, lies within this region but has no apparent gravity expression (probably because of the coarse distribution of gravity stations). Similarly, the Needles fault zone (plate 3) is not associated with a gravity anomaly. The fault system is thought to be related to salt flowage and/or downdip sliding of the post-salt sediments (Stromquist, 1976; Huntoon, 1979).

Gibson Dome lies along the northwestern flank of a linear zone of three circular magnetic highs. Only the southeastern most of the three magnetic highs is related to a moderate-amplitude gravity high. The northern boundary of the zone of magnetic highs is part of a continuous arcuate magnetic lineament (fig. 6, plate 3) that trends westward from Lisbon Valley anticline, to the region between Rustler Dome and Gibson Dome, and then west-southwest to about longitude $110^{o}25'$W. The prominent lineament is interpreted as a lithologic boundary separating a southern region, characterized by Precambrian rocks having moderate or strong magnetization, from a northern region, typified by basement rocks of weak magnetization. The absence of a corresponding gravity lineament may be due to a small density contrast across the lithologic boundary or to masking gravity effects of local depositional thickening and thinning of the Paradox evaporites.

The three magnetic highs trending west-northwest into the Gibson Dome area require additional discussions because of their alignment and geometric configurations. The circular patterns of these highs suggest that they reflect intermediate to mafic intrusions, similar to those lying northwest and northeast of Lockhart basin. The highs are less intense but may have deeper depths of burial than those near Lockhart Basin. The linearity of the zone of highs may indicate the presence of a deep-seated fault that provided a channel-way for ascending magma or the presence of a zone of weakness which localized intrusive activity. Alternative interpretations of the three magnetic highs are also plausible. For example, magnetic basement may shallow beneath the highs, or rocks with higher susceptibilities unrelated to intrusive activity may produce the magnetic highs.

Gravity lineaments (fig. 5) east of Gibson Dome follow a broad, north-northwest-trending gradient that represents a zone of structural transition.

East of the zone, gravity lows are attributed to an increasing depth of the Precambrian surface and to an increasing thickness of Paradox evaporites. To the west, higher gravity intensities reflect shallower depths to Precambrian on the Monument Uplift.

Concluding Remarks

Analyses of the gravity and magnetic anomaly maps suggest that the Gibson Dome area like the whole Paradox Basin region, is characterized by a heterogeneous Precambrian basement. Of particular interest are magnetic and gravity highs that may reflect intermediate to mafic intrusions located north and southeast of Gibson Dome. Although other interpretations were discussed, the linearity of the zones of inferred intrusions may indicate structural control for their emplacement. For example, the highs trending northwest from the Lockhart anticline to the San Rafael Swell may delineate a linear zone of igneous intrusions (dioritic or gabbroic) emplaced along a deep-seated fault. The fault may have developed in Proterozoic time when major episodes of deformation on northwest-trending structures occurred (Tweto, 1980). The emplacement of the intrusions may have taken place during crustal extension events, related to northwest-trending structures, in Proterozoic (King, 1976; Tweto, 1980) or Cambrian (Wickham, 1978). Similarly, the zone of magnetic and gravity highs trending west-northwest into the Gibson Dome area may also delineate igneous intrusions associated with deep-seated faulting. Both the hypothetical fault zones (plate 3) transect topographic features (fig. 7). There is also no consistent pattern of lineaments, defined from remote sensing imageries (Friedman and Simpson, 1978; Woodward-Clyde Consultants, 1982a), that has a trend coinciding with that of the inferred fault zones. Recent fault movement is, therefore, not indicated in the trends of surface features. On the other hand, salt beds are plastic and may have absorbed most of the stress generated from crystalline basement.

The zone of igneous intrusions northwest of Lockhart Basin appears to be offset left-laterally by a northeast-trending transverse shear zone. The Gibson Dome area lies within the Colorado Mineral Belt (Warner, 1978; Tweto, 1980) which is characterized primarily by northeast-trending, strike-slip faults. There are a small number of Landsat lineaments that lie along the trend of the inferred fault zone (Friedman and Simpson, 1978; Woodward-Clyde Consultants, 1982a). The nearby Lockhart fault and Trough Springs Canyon fault also parallel the inferred shear zone.

A major lithologic boundary expressed in the magnetic data transects the region between Rustler Dome and Gibson Dome. The contact trends west from the Lisbon Valley anticline to the Gibson Dome area and then west-southwest for a distance of about 60 km. Precambrian rocks north of the lithologic boundary are interpreted as having weaker magnetic properties than those south of the boundary. The contact cuts across topographic features and may not be fault controlled.

From the above considerations, analyses of the gravity and magnetic data do not yield any direct evidence for the presence of tectonically active structures in the Gibson Dome area. Nevertheless, many of the interpreted structures and lithologic variations warrant additional study as they suggest possible tectonic instabilities and thus may influence the development for siting and constructing a nuclear waste repository. Of immediate importance is (1) the collection and detailed analyses of nonproprietary gravity data, (2) detailed analyses of magnetic data, and (3) electromagnetic and seismic studies which consider the crystalline basement features delineated from the gravity and magnetic data. Pertinent research areas for further consideration include identification of fault-bounded Precambrian contacts and clarification of the tectonic development of the two interpreted igneous intrusive zones.

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