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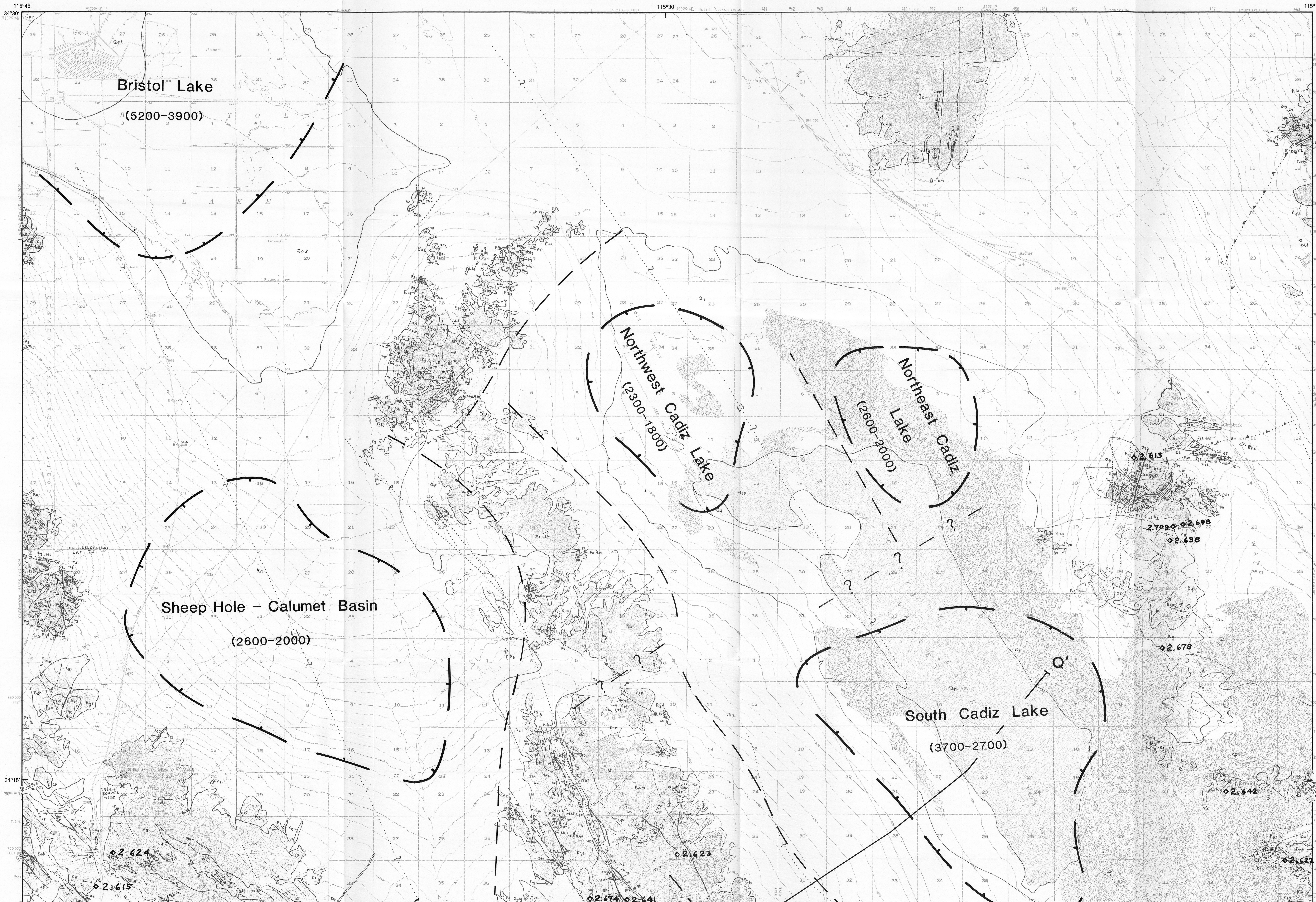


Base from U.S. Geological Survey, 1:62,500, Bristol Lake, Cadiz Lake, Cadiz Valley, Dale Lake, 1956.

APPROXIMATE MEAN DECLINATION, 1984

SCALE 1:62500

CONTOUR INTERVAL 80 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

AREA OF MAP

Geology from Howard and John (1984) with additions by K. A. Howard, Paul Stone, D. M. Miller

See sheet 2 for geologic explanation

## EXPLANATION

SEDIMENTARY BASIN--Approximately located. Inferred from gravity gradients

(4200–3100) MAXIMUM THICKNESS OF SEDIMENTARY SECTION--In basins, in feet, for density contrasts of 0.3 g/cm³ and 0.4 g/cm³, respectively

— — ?— PROMINENT GRAVITY GRADIENTS--Marking density contrasts across geologic contacts or structures. Questioned where uncertain

◇2.701 DENSITY DETERMINATION--In g/cm³

A——A′ GRAVITY PROFILE--See text

## GRAVITY DATA

Some 452 new gravity stations have been added to 91 already existing in the California gravity data file maintained by the U.S. Geological Survey (Snyder and others, 1982a,b) to produce the Bouguer gravity map of the Sheep Hole-Cadiz Wilderness Study Area displayed on sheet 3. Anomaly values were calculated using the 1967 Geodetic Reference System formula for theoretical gravity at sea level (International Association of Geodesy, 1971), and observed gravity values conform to the International Gravity Standardization Net of 1971 (Morelli, 1974). A standard Bouguer reduction density of 2.67 g/cm³ was used. All stations have been corrected for terrain effects from 166.7 km into 0.895 km from the station using an automatic terrain correction program of Plouff (1977). Stations in areas of rugged topography have been corrected by hand from 0.895 km into the station itself. The largest error in Bouguer gravity values is produced by uncertainties in elevations for some of the stations accessed by helicopter. This error probably does not exceed 5 milligals at worst, and none of the anomalies discussed in this report are controlled exclusively by such stations. Stations measured at bench marks or spot elevations and those which were measured at surveyed elevations have Bouguer values with uncertainties less than the 2-milligal contour interval. The principal facts for the stations and their estimated errors are detailed in Bracken and Simpson (1982).

## REGIONAL CONTEXT

The Bouguer gravity field in the study area has a maximum relief of 36 milligals, ranging from a low of -100 milligals over the center of Dale Lake to highs of -64 milligals in the Calumet Mountains and to the north of the Calumet Mountains. Highs of equal magnitude also occur in the Pinto Mountains in the southwest corner of the map, west of the Ship Mountains at the north end of the map, and in the northern Kilbeck Hills at the northeast corner of the map.

Notable features of the gravity field include the northwest-trending gravity high over the northern and southern Calumet Mountains and the more rounded gravity lows over alluvium-filled basins at Dale Lake, in the valley between the Sheep Hole Mountains and the northern Calumet Mountains, at Bristol Lake, and at the south end of Cadiz Lake. Unlike the Calumet Mountains, the Sheep Hole Mountains have little expression in the gravity field.

Most of the study area lies in a domain of low to moderate amplitude gravity anomalies, which includes almost all of the Mojave Desert north and east of the study area (Oliver, 1980; Oliver and others, 1980; Chapman and Rietman, 1978). If the anomalies have any trend at all, they generally trend northwest, which is congruent with the major structural trend (Jennings, 1977; Bishop, 1963). Gravity highs usually coincide with the ranges, and lows with the intervening alluvium-filled basins. South and west of the study area, just north of 34° latitude, there is a different structural domain defined by east-west trends (Jennings, 1977). The gravity field in this domain is also distinguished by the east-west elongation of anomalies (Oliver and others, 1980). The Dale Lake gravity low and the Pinto Mountain high in the southwest corner of sheet 3 are only small parts of larger east-west-trending gravity lows and highs. Both the east-west-trending structures and the east-west-trending gravity features in this zone are truncated by the southeastward extension of the structures which lie on both sides of the Sheep Hole Mountains.

## SEDIMENT-FILLED BASINS

Because the density contrast between sedimentary fill and crystalline bedrock is large, in general 0.3 to 0.5 g/cm³, it is not surprising that the basins coincide with the most prominent gravity anomalies (lows) on the map. Lack of information on the densities of the buried sedimentary materials, however, makes it difficult to estimate accurately the thickness of sedimentary deposits in the basins. These problems are discussed by Mabey (1956, 1960) and Rotstein and others (1976). Table 1 lists maximum depth estimates for all of the basins assuming infinite slab geometry and density contrasts of 0.3, 0.4, and 0.5 g/cm³. Because of compaction, 0.3 g/cm³ is probably closest to an average density for some of the deeper basins while 0.5 g/cm³ may best fit the smaller basins.

Depth estimates for the various basins obtained from other geophysical methods are also summarized in table 1. Estimates based on gravity are subject to uncertainties in density. Estimates inferred from aeromagnetic anomalies are subject to the availability of suitable anomalies in the basement and may give depths greater than basement depth if the magnetic sources are deep within the basement or shallower if the magnetic sources lie within the sedimentary section. Estimates of depth to resistive "electrical basement" (D. B. Hoover, oral commun., 1982) requires some measure of one-dimensionality (a layered earth) for the model assumptions to be totally valid, and resistive "electrical basement" need not be the same basement detected by other methods. Seismic refraction probably provides the most reliable estimates of depth to basement, but is subject to uncertainties introduced by assuming a simple layered earth model.

Figure 1 displays a two-dimensional gravity model generated by Stierman (1982) for line P-P′ in Dale Lake. This model fits the observed gravity data and has densities and interfaces consistent with the seismic refraction model described by Stierman (1982). A standard velocity-density relation (Woollard, 1962) was used to infer the density contrasts used. The refraction data were interpreted using a simple dipping layer solution even though complexities in the data suggest the presence of structural complications in the subsurface under the Dale Lake basin. Because of these complications, the seismic refraction model and the gravity model are at best an averaged representation of the physical properties along the length of the refraction line. The model suggests that an average density contrast of about 0.3 g/cm³ is required to fit the gravity data in this deep basin.

Figure 2 displays gravity data collected by the U.S. Geological Survey along profile Q-Q′, which runs east-northeast from the southern Sheep Hole Mountains, across Dry Lake, the southern Calumet Mountains, and ends in Cadiz Lake. The gravity low over Dry Lake requires 900 to 1600 ft of sedimentary fill (depending on density contrast - see table 1). An audiomagnetotelluric sounding gave a shallow depth to resistive electrical basement at Dry Lake (D. B. Hoover, oral commun., 1981), suggesting the absence of saline brines in this small basin. The presence of northwest-trending gradients on either side of this gravity low suggest a small graben structure. The graben floor must either ramp up to the northwest, or the graben must be terminated by cross structures, since the gravity field indicates very little sedimentary fill in the valley between the Sheep Hole Mountains and the Calumet Mountains just a few miles northwest of Dry Lake. A smaller low seen in figure 2 about 3.3 mi east-northeast of Dry Lake is seen as a deflection of contours on the gravity map (sheet 3). This low may reflect another smaller structurally-controlled depression filled with 500 to 1000 ft of sedimentary materials. It is possible that these small depressions and others like them in this area are formed by structures secondary to the main range-front faults, or as pull-apart structures formed in response to (right ?) lateral motion on northwest-trending faults in the valley between the Sheep Hole Mountains and the Calumet Mountains.

The gravity low over the south part of Cadiz Lake indicates about 3700 ft of fill (assuming an average density contrast of 0.3 g/cm³). Both gravity and aeromagnetic data (see sheet 2) are interpreted to signify that the south part of Cadiz Lake is deeper than the northern part.

The low labeled Northwest Cadiz Lake has an inferred maximum depth to basement of approximately 2300 ft for a density contrast of 0.3 g/cm³. This low appears to be an extension of the South Cadiz Lake low, and the two basins may connect in the subsurface. The small low labeled Northeast Cadiz Lake may have a maximum depth to basement on the order of 2600 ft. The small high immediately to the southwest and the sharp gradient in between are strongly suggestive of a northwest-trending structure. This low-high pair seems to be associated with a zone, which trends roughly northeast-southwest, of truncations and offsets of anomalies. Possible components of this trend are marked with question marks on the map.

The gravity low labeled Sheep Hole-Calumet Basin indicates a sedimentary section thickness of 2600 ft for a density contrast of 0.3 g/cm³. This basin may connect with Bristol Lake in the shallow subsurface, but the gravity field suggests the existence of a basement barrier at deeper levels between these two basins. Additional gravity data are needed to better define this possible barrier.

The presence of economically important brine deposits in Dale Lake, Bristol Lake, and Cadiz Lake raises the possibility that the extension of these basins into the Sheep Hole-Cadiz Wilderness Study Area may have economic potential (Marsh and others, 1982). Parts of the Dale Lake, Cadiz Lake, and Sheep Hole-Calumet basins, as defined by gravity lows indicating sedimentary section thickness in excess of 1000 ft, lie within the study area. Electrical soundings reported by D. B. Hoover (written commun., 1982) are consistent with the presence of low conductivity brines in these areas. However, the marginal areas of these basins will probably contain a higher proportion of coarser sedimentary facies derived from the erosion of the nearby ranges that may make the extraction of such brines more difficult than in the centers of the basins.

## BEDROCK AREAS

Densities for igneous rocks in the study area, compiled by Keith Howard (written commun., 1981), are tabulated in table 2 and are indicated on sheet 4. Most of the exposed rock consists of Mesozoic granites and granodiorites with densities between 2.6 and 2.7 g/cm³. Minor amounts of metamorphosed older rock occur as inclusions in the granites. Exposures of Precambrian gneisses occur in the northernmost Calumet Mountains, along with minor amounts of Tertiary volcanic and igneous rocks. Similar Precambrian gneisses in other parts of the Mojave Desert have densities ranging from 2.6 to 2.8 g/cm³.

The gravity profile Q-Q′ (fig. 2) requires a body with a positive density contrast under the Calumet Mountains. The actual shape or thickness of the dense mass cannot be determined with any great accuracy from the gravity data alone, but the absence of a similar gravity high over the Sheep Hole Mountains suggests that the underpinnings of that range are quite different.

The Sheep Hole Mountains have little gravity expression relative to the valley area to the east, which is to be expected if the sedimentary sections in the valley are quite shallow and the valley is underlain by rocks of density similar to those exposed in the Sheep Hole Mountains. (Calculations of the Bouguer anomaly field has removed the effects of topography assumed to have a density of 2.67 g/cm³.) The gravity high associated with the Calumet Mountains is unexpected, since the granitic rocks exposed here have densities not much different from those exposed in the Sheep Hole Mountains. There are, however, large mafic metamorphosed inclusions in the southern Calumet Mountains and areas of exposed Precambrian bedrock in the northern Calumet Mountains. The inclusions suggest proximity to the wall or floor of the batholith--an observation supported by some steep aeromagnetic gradients in the southern Calumet Mountains (sheet 1), the gradients having no explanation in the exposed granitic rocks.

Gravity highs similar in magnitude to the one that occurs over the Calumet Mountains occur over other ranges to the north and east. If the intervening lows caused by alluvium-filled valleys were removed, there would be a single broad high encompassing the Calumet Mountains, the Old Woman Mountains, and the Iron Mountains (Chapman and Rietman, 1978). These ranges expose Precambrian and Paleozoic basement rocks, and also coincide with a broad aeromagnetic anomaly high (sheet 1). We infer that these ranges all share a common Precambrian basement terrane, while the Sheep Hole Mountains, which lack both the coherent gravity and aeromagnetic highs and exposed Precambrian rocks, have a different basement. This observation, if correct, suggests that important structures run through the valley between the Sheep Hole and Calumet Mountains.

Other geophysical evidence also supports the existence of an important crustal boundary trending roughly north-northwest in this vicinity. Teleseismic P-delays (Hadley and Kanamori, 1977), apparent depth to Moho from seismic refraction profiles (Fuis, 1981), and heat-flow values (Lachenbruch and others, 1978; Lachenbruch and Sass, 1981) all show abrupt changes near the Sheep Hole Mountains. Although none of these data presently allow great precision in the location of the boundary, the gravity and aeromagnetic data described in this report suggest that the Sheep Hole Mountains have anomalies which differ from those observed over ranges to the north and east and that the crustal boundary may lie between the Sheep Hole and Calumet Mountains.

## STRUCTURAL TRENDS

Gradients in the gravity field mark density contrasts in the rocks that are often geologic contacts including structural boundaries. Gradients that are reasonably controlled by observations are marked on the map as dashed lines. East-west gradients lie along the north and south sides of Dale Lake and the fault-bounded northern front of the Pinto Mountains. Northwest-trending gradients lie over parts of both the eastern and western sides of the Sheep Hole Mountains and the Calumet Mountains near mapped range front faults. The absence of gradients does not, of course, imply the absence of structure--only the absence of density contrasts. The gravity gradients on the northeast sides of these two ranges seem to be more continuous and to be closer to the range fronts than the gradients on the southwest sides. The northwest-southeast trend is also apparent on the aeromagnetic map (sheet 2) as a prominent set of gradients and magnetic low anomalies of regional extent. Faults in the northern Sheep Hole Mountains that are part of this trend show indications of mineralization (Marsh and others, 1982). It is possible that gradients farther to the south on both sides of the Sheep Hole Mountains may overlie faults that by analogy might also be mineralized. However, the gravity data tell nothing absolute about the presence or value of mineralization along such gradients. The interesting discordant north-south gradient near the northwest end of the southern Calumet Mountains has a counterpart gradient in the aeromagnetic data. There are also indications that the southwest trending zone mentioned earlier than seems to cross Cadiz Lake may continue across the map area. No single gradient or anomaly extends for the entire distance, but short gradients, offsets, small anomalies and terminations seem to mark such a northeast-southeast zone. This northeast trend is subparallel to similar trends seen in the aeromagnetic anomalies of the Needles 1° by 2° sheet (U.S. Geological Survey, 1981), where these trends are thought to mark a major basement fracture system. The extrapolations of two such trends into the study area are indicated on sheet 2 as trend 3 and trend 4. Trend 4 most closely parallels the gravity trend described above.

## CONCLUSIONS

Gravity lows in the valleys between ranges are caused by low density sedimentary materials filling basins that are probably bounded by structures in many cases. The thickness of sedimentary deposits in these basins can be estimated from the amplitudes of the gravity lows by assuming a reasonable density for sedimentary materials. The Dale Lake and Cadiz Lake basins give thickness estimates ranging from 1400 to 4200 ft. The basin between the Sheep Hole and North Calumet Mountains, which may be an extension of the Bristol Lake basin, gives thicknesses in the range from 1600 to 2600 ft. The parts of these basins that lie within the wilderness study area may have resources of saline brines. Smaller basins between the Sheep Hole and South Calumet Mountains such as the one under Dry Lake have sediment thicknesses which reach 1600 ft, but the brine potential is considered to be low.

Gravity highs over the Calumet Mountains are of similar magnitude and character to highs found over neighboring ranges to the north and east. This implies that the Calumet Mountains share a Precambrian basement with these ranges, while the Sheep Hole Mountains, which have no such coherent gravity high associated with them, may have a different basement. Teleseismic P-delays, apparent Moho velocities, and heat flow measurements reported by other investigators also point to an important crustal boundary roughly in the position of the Sheep Hole Mountains.

Steep linear gradients in the gravity field indicate density contrasts probably produced by structures in many cases. East-west-trending gradients, parallel to trends in the Pinto Mountains, are found in the southwest corner of the study area near Dale Lake. Northwest-southeast-trending gradients occur on both sides of the Sheep Hole and Calumet Mountains. These gradients parallel a regional structural trend that extends both northwest and southeast of the study area. Some of these northwest-southeast faults in the northern Sheep Hole Mountains show signs of mineralization.

## ACKNOWLEDGMENTS

We thank the operators of the brine evaporating enterprises on Cadiz Lake and Dale Lake for permission to use their roads in collecting gravity and seismic data.

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Table 1.--Maximum depth estimates for all basins from various geophysical methods

| | Milligals relative to bedrock | Gravity depth (ft) Density 0.3 | Contrast 0.4 | (g/cm³) 0.5 | Aeromagnetic depth (ft) | Electrical[1] depth (ft) | Seismic Refraction depth (ft) |
|---|---|---|---|---|---|---|---|
| Dale Lake | -16 | 4200 | 3100 | 2500 | 1000-3000 | 650[2] | 3800-2700 B-B′ 6800-3400 A-A′ |
| Sheep Hole-Calumet Basin | -10 | 2600 | 2000 | 1600 | 2300 ? | (1300)[3] | --- |
| Bristol Lake | -20 | 5200 | 3900 | 3100 | 2400+ | --- | --- |
| South Cadiz Lake | -14 | 3700 | 2700 | 2200 | 2200-2400 | (>2600) | --- |
| Northwest Cadiz Lake | - 9 | 2300 | 1800 | 1400 | 400 | (2000) | --- |
| Northeast Cadiz Lake | -10 | 2600 | 2000 | 1600 | --- | --- | --- |
| Dry Lake | - 6 | 1600 | 1200 | 900 | --- | --- | --- |

[1] Electrical basement is not necessarily geologic basement.
[2] Near north end of lake close to seismic line B-B′.
[3] Parentheses indicate that electrical sounding is nearby.

Table 2.--Densities of various rock types

[Compiled by K. A. Howard]

| Sample No. | Long | Lat | Density (g/cm³) | Rock type |
|---|---|---|---|---|
| CX374 | 115.4064 | 34.0925 | 2.628 | monzogranite |
| CX380 | 115.5161 | 34.2114 | 2.641 | monzogranite |
| CX381 | 115.5089 | 34.2067 | 2.662 | monzogranite |
| CX382 | 115.5058 | 34.2025 | 2.632 | monzogranite |
| CX384 | 115.4322 | 34.1544 | 2.628 | monzogranite |
| CX397 | 115.4967 | 34.2261 | 2.623 | monzogranite |
| KI244 | 115.2828 | 34.2469 | 2.642 | monzogranite |
| KI267 | 115.3050 | 34.3286 | 2.638 | monzogranite |
| CX375A | 115.5306 | 34.2114 | 2.674 | augen gneiss |
| CX400 | 115.4658 | 34.1939 | 2.749 | gneiss |
| IM242 | 115.2600 | 34.2244 | 2.644 | gneiss |
| IM242A | 115.2600 | 34.2244 | 2.622 | gneiss |
| IM029A | 115.2597 | 34.0964 | 2.624 | gneiss |
| SH064 | 115.6756 | 34.1856 | 2.690 | gneiss |
| KI359 | 115.3192 | 34.3556 | 2.613 | granite |
| OW473 | 115.2575 | 34.4653 | 2.617 | granite |
| SH191 | 115.7156 | 34.2264 | 2.674 | granite |
| KI263 | 115.3000 | 34.3339 | 2.698 | granodiorite |
| KI126 | 115.3039 | 34.3331 | 2.709 | granodiorite |
| SH033 | 115.5675 | 34.1186 | 2.701 | granodiorite |
| SH033 | 115.5603 | 34.0956 | 2.658 | granodiorite |
| CA199 | 115.5972 | 34.4383 | 2.813 | monzodiorite |
| KI128 | 115.3081 | 34.2936 | 2.678 | monzogranite |
| SH190 | 115.7222 | 34.2156 | 2.615 | monzogranite |
| SH126 | 115.7236 | 34.2006 | 2.648 | quartz monzonite |
| SH053 | 115.7233 | 34.2072 | 2.643 | quartz monzonite |
| SH034 | 115.5622 | 34.0919 | 2.619 | syenogranite |
| Average | | | 2.659 g/cm³ | |

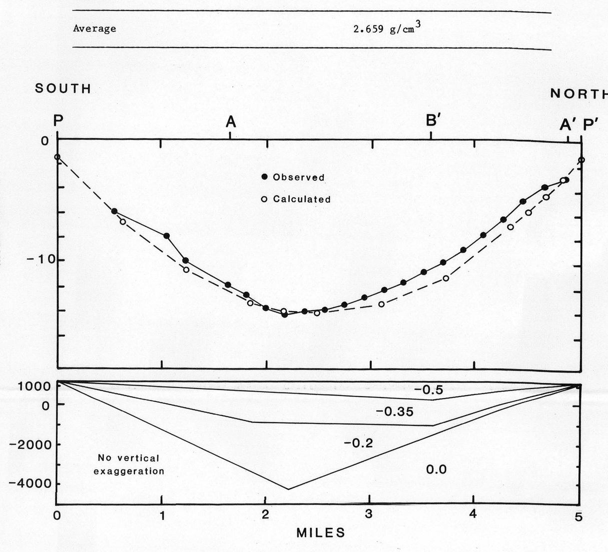



Figure 1. Two-dimensional gravity model along line P-P′ in Dale Lake, from Stierman (1982). Densities and interface depths constrained to satisfy the seismic model generated by Stierman (1982). Density contrasts are relative to the reduction density of 2.67 g/cm³.

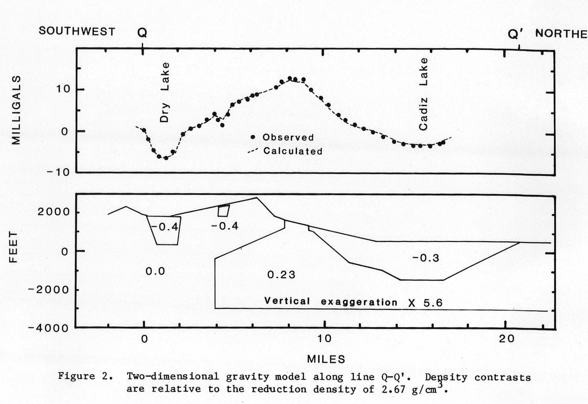
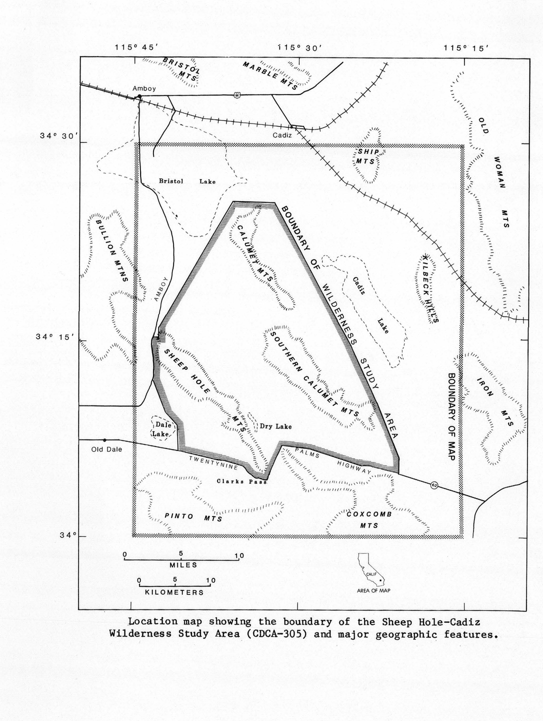



Figure 2. Two-dimensional gravity model along line Q-Q′. Density contrasts are relative to the reduction density of 2.67 g/cm³.




Location map showing the boundary of the Sheep Hole-Cadiz Wilderness Study Area (CDCA-305) and major geographic features.

INTERPRETATION OF BOUGUER GRAVITY MAP

# AEROMAGNETIC, BOUGUER GRAVITY, AND INTERPRETATION MAPS OF THE SHEEP HOLE–CADIZ WILDERNESS STUDY AREA (CDCA–305), SAN BERNARDINO COUNTY, CALIFORNIA

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1984

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INTERIOR—GEOLOGICAL SURVEY, RESTON, VIRGINIA—1984