Gravity Survey of the Western Mojave Desert California

By DON R. MABEY

GEOPHYSICAL FIELD INVESTIGATIONS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 316-D

A study of the relation of the gravity anomalies to the geology with special reference to the distribution and thickness of the Cenozoic rocks

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1960

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

GRAVITY SURVEY OF THE WESTERN MOJAVE DESERT, CALIFORNIA

By Don R. Mabey

ABSTRACT

The western Mojave Desert lies in the southwest corner of the Basin and Range province between the San Andreas and Garlock fault zones. The region is characterized by low hills exhibiting no pronounced trends and by closed alluvium-covered basins. It is underlain by a pre-Tertiary basement complex composed of plutonic igneous rocks enclosing pendants of metamorphic rocks. The basement complex is overlain by folded, faulted, and eroded remnants of sedimentary, pyroclastic, and volcanic rocks of Tertiary age which were deposited in local basins. Alluvial sediments of Quaternary age cover nearly all the valley areas.

The density contrast that exists in the western Mojave Desert between the Cenozoic rocks and pre-Cenozoic rocks produces gravity anomalies that can be readily defined by gravity surveys. Gravity anomalies resulting from density variations within the pre-Cenozoic basement complex are also evident. To define the major gravity anomalies, a gravity survey consisting of 1,900 gravity stations was conducted over the western Mojave Desert. The data are reduced to the complete Bouguer anomaly and presented on a contour map along with the generalized geology.

The gravity anomaly map indicates the areas in which the basement complex is overlain by large thicknesses of Cenozoic deposits and the order of magnitude of the depth to the basement complex. Gravity anomalies are associated with several major faults. Along profiles across seven major gravity lows, two-dimensional theoretical analyses are presented to show the distribution of Cenozoic deposits that could produce the measured anomaly. Lateral density variations within the Cenozoic deposits complicate the interpretation of the anomalies.

Just southeast of the Garlock fault zone the gravity anomalies trend generally parallel to the fault zone. Two major areas of subsidences are indicated along the Garlock fault zone northeast of Tehachapi Pass. One of the subsidences, in Cantil Valley, is estimated to contain about 2 miles of Cenozoic rocks. In the western part of Antelope Valley, near the junction of the Garlock and San Andreas fault zones, there is a major east-trending gravity low. The gravity contours in the region of the San Andreas fault zone trend generally parallel to the fault zone, but no important local anomalies associated with the fault zone were recognized. Southeast of Rosamond Lake there is a major gravity low trending east-northeast. An extensive irregularly shaped gravity low occurs north of Cajon Pass. In the central part of the surveyed area there are several anomalies of smaller areal extent and varying trends.

Information inferred from the gravity data relative to the distribution of the Cenozoic deposits and the structural features effecting these deposits is an aid to the development of the ground-water resources of the region and in exploration for saline deposits in the Cenozoic section. This same information will be helpful in evaluating the possibility of whether important petroleum deposits may occur in the western Mojave Desert.

INTRODUCTION

LOCATION AND CULTURAL FEATURES

The western Mojave Desert is in southern California (fig. 22) in parts of Los Angeles, Kern, and San Bernardino Counties. It lies in a westward-pointing wedge formed by the junction of the San Andreas and Garlock fault zones. The region is bounded on the northwest and north by the Tehachapi Mountains, the Sierra Nevada, and the El Paso Mountains and on the south and southwest by the Transverse Ranges. The eastern boundary is not clearly defined but for this study is approximately longitude 117° west, which lies just east of Barstow. East of this line the mountain ranges become more prominent.

The principal towns are Lancaster, Palmdale, Mojave, Barstow, and Victorville. Several major highways cross the region, including U.S. Highways 66, 466, 91, 395, and 6. The Atchison, Topeka and Santa Fe Railway, the Union Pacific Railroad, and the Southern Pacific Lines serve the region. The industries include agriculture, manufacturing, mining, and activities associated with the several defense department installations. Most of the agricultural developments are dependent upon irrigation. As in most arid regions, water is a critical item. The limits to which the region can be developed are dependent upon the availability of water for industrial, agricultural, and household uses.

Annual precipitation is less than 6 inches over most of the Mojave Desert. Near the bordering mountains the precipitation increases, and areas in the San Ber-

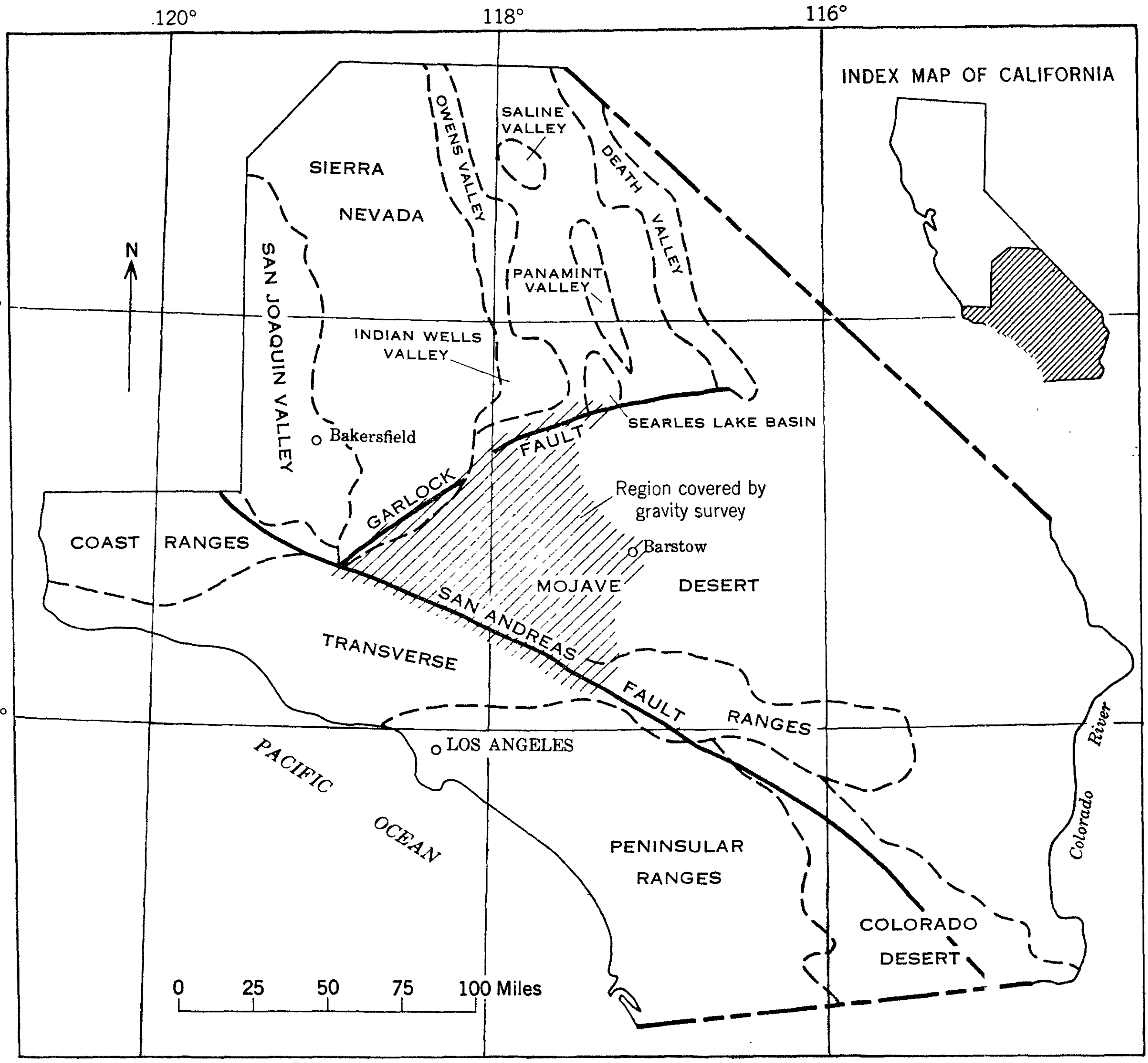

FIGURE 22.—Index map of southern California showing area of this report in relation to the Mojave Desert and other physiographic features.

nardino Mountains receive more than 40 inches annually. The summers are hot and daytime temperatures of more than 100° are common. Minimum winter temperatures are as low as 10°.

Important deposits of borates, tungsten, limestone, gold and silver have been developed in the western Mojave Desert. At present the borate deposit at Boron is the leading source of borate minerals in the world. Limestone produced from pre-Tertiary deposits is used in the manufacture of cement, as an agricultural mineral, and as a metallurgical flux. Gold and silver have been mined extensively in the past in the Rosamond-Mojave area and in the Randsburg-Red Mountain area; however, the current production is small. The tungsten deposits at Atolia, now largely inactive, have been a major source of tungsten.

PURPOSE OF GEOPHYSICAL INVESTIGATIONS

The need for some method of obtaining subsurface information on the Cenozoic geology is very important in the western Mojave Desert because an extensive cover of Quaternary sediments obscures much of the rather complex Tertiary geology. In 1953 the U.S. Geological Survey tested several methods of geophysical exploration in the desert areas of southern California in an effort to determine which of the various methods were useful in studying the geologic problems of the region. Seismic reflection and refraction, ground and airborne magnetic, and gravity methods were tested under a variety of conditions. The data collected during these tests indicate that the seismic methods are generally useful in the areas of the present playas and that both reflection and refraction techniques yield information on the thickness, structure, and stratigraphy of the basin fill. Fault traces were located in areas removed from the playas by seismic-refraction techniques, but the general heterogeneous nature of the Cenozoic fill and adverse near-surface conditions severely limit the usefulness of seismic exploration. The magnetic anomalies associated with Tertiary volcanic rocks occasionally yielded information relative to the Cenozoic fill, and some anomalies can be interpreted in terms of the depth of the basement surface and intrabasement compositional variations. The density contrast between the Cenozoic sediments and the pre-Cenozoic basement rocks produces gravity anomalies that are useful in studying the Cenozoic geology. Some regional structural trends are also indicated by the gravity anomalies.

As a result of these tests the regional gravity survey, which is the subject of the present report, was conducted over the western Mojave Desert during two 4-month winter field seasons in 1953, 1954, and 1955. The purpose of the survey was to apply the technique of gravity exploration to obtain subsurface information in a study of the geology of the western Mojave Desert. The gravity study was coordinated with other geologic investigations being conducted by the U.S. Geological Survey in the Mojave Desert.

ACKNOWLEDGMENTS

L. C. Pakiser, Jr., U.S. Geological Survey, was largely responsible for outlining the procedures used in the gravity survey. He supervised all phases of the work and assisted the author in an advisory capacity. T. W. Dibblee, Jr., also of the Survey, provided geologic guidance and advice and furnished unpublished geologic data to assist in guiding the fieldwork and interpreting the gravity data.

PHYSICAL AND GEOLOGIC FEATURES

PHYSIOGRAPHY AND DRAINAGE

The surface features of the Mojave Desert are distinctly different from those of the adjoining regions to the north and south, and therefore the desert area is considered by some to be a separate province (Jahns, 1954, p. 13). The western part of the Mojave Desert stands out as an area of only moderate relief in contrast to the areas to the north, west, and south. There is no apparent pattern to the trend of the isolated hills that rise above the gently eastward-sloping plain. In contrast, the Sierra Nevada to the northwest, the Transverse Ranges to the south, and the part of the Basin and Range province north of the Garlock fault show strong relief and well-defined trends.

The western Mojave Desert is for the most part an undrained alluvium-covered plain that is separated into valleys or closed basins by isolated hills, groups of hills, and some low mountains. The bottoms of the closed basins have playas which contain water only after occasional heavy rains. The only major surface drainage channel is the Mojave River, which starts in the San Bernardino Mountains and flows northward, mostly underground, thence eastward through the central Mojave Desert to Soda Lake.

The lowest point in the surveyed region is about 1,900 feet above sea level at Koehn Lake in Cantil Valley. The relief is low to moderate in most of the region, and altitudes range between 1,900 to 4,000 feet. There are several hills within the desert area higher than 4,000 feet; the highest is Red Mountain at an altitude of 5,220 feet. Mount San Antonio in the San Gabriel Mountains to the south rises to an altitude of 10,080 feet, and Double Mountain in the Tehachapi Mountains to the northwest rises to an altitude of 7,998 feet.

GEOLOGY

The western Mojave Desert is underlain by a pre-Tertiary crystalline basement complex composed largely of plutonic igneous rocks enclosing pendants of metasedimentary and metavolcanic rocks. The basement complex is in places overlain unconformably by nonmarine sedimentary, pyroclastic, and volcanic rocks of Tertiary age, mostly deposited in local basins. The Tertiary rocks are locally deformed and cut by volcanic intrusions. The pre-Tertiary and Tertiary rocks are overlain unconformably by alluvial sediments of Quaternary age that cover nearly all the valley areas.

The pre-Tertiary metamorphic rocks occur as large roof pendants or blocks partly engulfed by Mesozoic plutons. They are largely much metamorphosed, are complexly folded and faulted, and contain few recognizable fossils. The age of the oldest rocks has not been reliably determined. Referring to the strongly foliated schists and gneisses of unknown age, McCulloh (1954, p. 15) states:

> They have been termed pre-Cambrian by various investigators because of these similarities, or because of their petrologic contrasts with known Paleozoic metamorphic rocks. Although these age assignments may prove to be correct in some or all instances, it should be kept in mind that, at present, trust-

worthy stratigraphic evidence of pre-Cambrian age is lacking in the central and western Mojave Desert.

From the data that are available it seems that the bulk of the pre-Tertiary metamorphic rocks are Paleozoic. The Oro Grande series in the Barstow quadrangle has been described by Bowen (1954, p. 34) as most probably Carboniferous. Bowen concludes that the Fairview Valley formation in the Barstow quadrangle is Permian, but McCulloh considers that the available evidence permits assignment to either the Mesozoic or the Permian.

Nonmarine sedimentary and volcanic rocks of Miocene and Pliocene age crop out at scattered places in the western Mojave block and probably underlie much of the alluvium-covered valleys. The thickest exposed section occurs at the west end of Antelope Valley where some 8,000 feet of volcanic (andesitic) and clastic sedimentary strata are upturned adjacent to the San Andreas fault and dip steeply into a syncline plunging easterly into Antelope Valley. Southeastward along this fault are fault grabens of severely deformed terrestrial sedimentary strata of Miocene and Pliocene age, and at Cajon Pass some 6,000 feet of these strata are exposed dipping northerly under the alluvium-covered southern rim of the Mojave Desert (Dibblee, written communication, 1957).

Several thousand feet of moderately deformed terrestrial sedimentary rocks of Pliocene age, which include andesitic volcanic rocks in the Lava Mountains, is exposed in and just south of the Garlock fault zone.

Farther out in the western Mojave Desert, away from its bounding faults, are scattered outcrops of moderately deformed nonmarine sedimentary and volcanic rocks of supposed Miocene and Pliocene age, which have a total exposed thickness of about 2,000 feet. Silicic pyroclastic and volcanic rocks and some conglomerates make up the lower part of this series; fluviatile and lacustrine sedimentary rocks make up the upper part; and within the series there are local flows of basalt. These rocks crop out in Antelope Buttes, Rosamond Hills, hills bordering the Kramer borate district, and in the Kramer Hills. In the hills north and east of Harper Valley a similar series of these rocks is exposed, also moderately deformed, but they have a maximum exposed total thickness of some 5,000 feet. In the valley areas in the vicinity of these exposures the Tertiary rocks are buried by Quaternary deposits. In the southern part of the western Mojave Desert east of Antelope Valley rocks of Tertiary age are notably absent, at least in the highland areas (Dibblee, written communication, 1957).

Mesozoic plutonic igneous rocks underlie large areas of the western Mojave Desert. The composition ranges from nearly ultramafic to very silicic. McCulloch (1954, p. 21) reports "on the basis of reconnaissance observations, that leucocratic quartz monzonite or granite has an areal abundance many times greater than that of any other intrusive rock type, and that diorite and gabbro are far less abundant." These rocks seem to be spatially and mineralogically related to, and about the same age as, the plutonic igneous rocks of the Sierra Nevada and Peninsular Ranges (McCulloh, 1954, p. 20). Quartz monzonite is notably less predominant or even subordinate to other, less silicic crystalline rocks in areas adjacent to the Mojave block. The pre-Tertiary crystalline complex of the mountain area southwest of the San Andreas fault, and in the Tehachapi Mountains northwest of the Garlock fault, is composed mainly of quartz dioritic plutonic and gneissic rocks and several large bodies of mica schist.

Deposits of Quaternary age consisting of alluvial detritus derived largely from the mountains bordering the western Mojave Desert, and to a lesser extent from the highlands within it, fill all the valley areas, in places to depths of more than 1,000 feet. This alluvial material covers the major part of the western Mojave Desert and conceals most of the Tertiary and pre-Tertiary rocks upon which it lies uncomformably. Northeast of Harper Lake the Quaternary deposits include an extensive lava flow of basalt as thick as 150 feet. The Quaternary deposits are generally undisturbed, but in places they are slightly elevated and dissected, and along or near major faults they are deformed.

Although the Goler formation of Eocene age (Hewett, 1954a, p. 15) crops out just north of the Garlock fault and sedimentary rocks considered to be Eocene crop out just south of San Andreas fault, no rocks of Eocene or Oligocene age have been recognized in the western Mojave Desert. This apparent absence of Eocene and Oligocene sediments is an indication that the western Mojave Desert was subjected to active erosion during this time and that the products of erosion were removed from the area (Hewett, 1954a, p. 15).

Apparently during Miocene time local erosion occurred with depositions in local basins. Local erosion and internal drainage continued in early and middle Pliocene time. The late Pliocene was a time of erosion and external drainage. Erosion continued through the Quaternary period, accompanied in the western Mojave Desert by internal drainage during at least late Pleistocene and Recent time (Hewett, 1954a, p. 19). Today, the Mojave block has reached a stage of later maturity to old age in the erosion cycle.

The San Andreas and Garlock faults, which form the general boundaries of surveyed area to the north, west, and south, are two of the most important structural features in southern California. Much study has been devoted to the San Andreas fault and, to a lesser degree, the Garlock fault, but many important questions remain unanswered.

The San Andreas fault has been mapped for a distance of about 500 miles from Point Arena almost to the Mexican border. Hill and Dibblee (1953, p. 445) summarize their beliefs as follows:

1. The San Andreas is a steep fault zone of variable width consisting of one or several nearly parallel faults.
2. Its inception was quite likely pre-Tertiary, and it is now active.
3. It has probably been characterized by right-lateral displacements throughout its history.
4. It marks such an important contact that rarely can it be crossed, except in Recent alluvium, without passing into significantly different rocks.
5. Its cumulative displacement of some rock units is at least tens of miles, and older rocks may have been displaced a few hundred miles.

The Garlock fault extends northeast and east-northeast for about 150 miles from its junction with the San Andreas fault near Tejon Pass. The Garlock fault is similar in many respects to the San Andreas fault; however, the movement along the Garlock fault is left lateral. Thus, the Mojave block lying between the two fault zones has moved to the east relative to regions to the north and south.

In the western Mojave Desert there are many closely spaced high-angle northwest-trending faults oriented approximately parallel to the San Andreas fault. The vertical displacement along the faults often is reversed over an interval of a few miles resulting in a scissors pattern. On some of these faults there is suggestive to definite evidence of small right-lateral displacements.

GRAVITY SURVEY

FIELDWORK AND REDUCTION OF DATA

The primary objective of the fieldwork was to compile a regional gravity map that would define the general characteristics of the gravity anomalies associated with areas of thick Tertiary and Quaternary deposits and to outline regional gravity variations from influences within the pre-Tertiary basement complex. Undoubtedly many small anomalies that were not detected by the station density of the survey exist in the region, and more detailed work would alter to some degree the presentation of the major anomalies as here represented.

The general procedure was to establish gravity stations at points where horizontal and vertical position has been established by previous surveying of the U.S. Geological Survey, U.S. Coast and Geodetic Survey, the U.S. Army Corps of Engineers, and other Government and private organizations. The data from gravity stations thus established indicated the location of the major anomalies. The gravity crew then obtained, using planetable and transit surveys, the horizontal and vertical position on the additional gravity stations necessary to define the gravity anomalies in the detail considered desirable. The elevations at the gravity stations used in reducing the gravity data are considered to be accurate to within 4 feet. Nearly all the elevations are accurate to within 2 feet. The accuracy with which the horizontal position of the gravity stations are known is dependent in part upon the accuracy of the topographic maps of the particular area. The position of each gravity station is considered to be determined within 250 feet relative to adjoining stations; however, the absolute location may be in error by a larger amount. A change of 4 feet in the assumed elevation of a gravity station would alter the Bouguer anomaly by 0.24 milligal. A north-south change of 250 feet in the assumed position of a station would change the anomaly value by 0.06 milligal.

Gravity observations were made at about 1,900 stations. A Frost temperature controlled gravimeter with a scale constant of 0.0729 milligal per scale division mounted in a four-wheel drive station wagon and a Worden gravimeter with a scale constant of 0.505 milligal per scale division were used. The operation of a gravimeter and an explanation of the units used in gravity exploration are described in geophysic textbooks, such as Nettleton (1940) and Dobrin (1952). The observed gravity values are referenced to a gravity network that includes several U.S. Coast and Geodetic Survey's pendulum stations and several base stations established by Woollard. Twenty-seven base stations were established over the region as the fieldwork progressed by making at least three repeat readings at each station relative to a previously established base station. The gravity stations were established, using a single-loop method. The same base station was read at the beginning and end of each loop, and a reading was repeated at a station of a previous loop. The repeat reading provided a measure of the accuracy of the gravity observation. The relative observed gravity determined at the gravity stations is considered to be accurate to within 0.2 milligal.

528174—60——2

The gravity data are reduced to the complete Bouguer anomaly by methods described in textbooks, such as Nettleton (1940). An elevation-correction factor of 0.06 milligal per foot, which approximately corresponds to an assumed density of 2.67 g per cm^3 (grams per cubic centimeter), was used over the entire area of the survey. Variations in the total terrain effect are small over most of the central parts of the surveyed area. The terrain effect inceases toward the mountains where there is a maximum effect of about 10 milligals. The terrain effect was computed, using the U.S. Coast and Geodetic Survey system (Swick, 1942) and assuming a density of 2.67 g per cm^3, for 215 stations (mostly in areas of large relief) through the zones where the variations were large. The terrain corrections for the remaining stations were interpolated. The terrain corrections thus determined through zone O (about 100 miles radius) are believed to be correct to within 10 percent of the total terrain effect or 0.2 milligal, whichever is larger.

BOUGUER ANOMALY MAP

To illustrate the gravity anomalies, 1,000 milligals was added to the complete Bouguer anomaly values to make all the values positive. Such a presentation facilitates the study of the local anomalies while the absolute complete Bouguer anomaly values are still apparent. The Bouguer anomaly map (pl. 10) shows the anomaly values contoured at a 2-milligal interval superimposed upon a generalized geologic map. The geology on the map is intended to show only the approximate location and extent of major outcrops and structural features.

In the western Mojave Desert gravity lows relative to adjoining areas were observed in all places where important thicknesses of Cenozoic fill are known to exist. The Bouguer anomaly map shows the location and relative magnitude of the thickness of the major Cenozoic deposits. Several important structural features are indicated on the anomaly map. Several gravity anomalies of large areal extent reflect intrabasement features.

Along the San Andreas fault zone the gravity contours trend generally parallel to the fault zone. The trends appear to be in part related to extensive intrabasement anomalies not defined by the data collected in the western Mojave Desert. The Garlock fault zone northeast of Tehachapi Pass has pronounced gravity expression resulting from depressions that have developed along and within the fault zone. For several miles to the south of the Garlock fault the major gravity features trend generally parallel to the Garlock fault. In areas removed from the San Andreas and Garlock fault zones, the direction of the gravity trends are less consistent. A northwest trend parallel to the northwest fault system is evident.

Intrabasement anomalies show only moderate relief over most of the western Mojave Desert; Bouguer anomaly values in basement outcrop areas range about −90 to −100 milligals. Two important exceptions exist. In the Frazier Mountain area and over the Sierra Pelona the values rise to −60 milligals with anomaly values increasing southwesterly at the limits of the surveyed area. Along the northwestern border of the surveyed area the bedrock anomaly values are less than −100 milligals; this is probably a manifestation of a major regional gravity low associated with the Sierra Nevada, which has been recognized by others (Oliver, 1956, p. 1724) and its significance will not be discussed here. In the San Bernardino Mountains the highest anomaly value observed was about −104 milligals; however, not enough data are available in this area to confirm the existence of an anomalous gravity variation.

The Sierra Pelona and Liebre Mountains constitute a structurally high mass of basement rock. The Sierra Pelona is made up almost entirely of Pelona schist (Precambrian?) (Bailey and Jahns, 1954, p. 99). The gravity high that the available data indicate is developing over the schist dominates a considerable area on the gravity-anomaly map of the Palmdale-Fairmont region of the Mojave block. An explanation of this gravity anomaly will not be attempted in this report because the anomaly lies largely outside the Mojave Desert and is for the most part a broad feature probably associated with thinning of the earth's crust toward the Pacific Ocean.

PROBLEMS OF INTERPRETATION

Areas of great geologic interest exist where information inferred from the gravity data is lacking or is inconclusive. Using gravity data alone, it is generally not possible to differentiate between different types of Cenozoic rocks. If a near-ideal situation existed it would be possible to determine the approximate density of the Cenozoic rocks and thus infer something about the rock type; however, it is not usually possible to do this.

Structures which do not affect the relative vertical position of materials of appreciable different densities will not produce gravity anomalies. Thus, structures affecting only intrabasement rocks may not be indicated by the gravity data. Likewise, features within the Cenozoic section such as saline deposits and water-producing strata will not generally be directly detected by gravity observation.

Although the extent of important accumulations of Cenozoic rocks can be inferred from the gravity data, it is not possible to define the limits of the basins in which the rocks were originally deposited. Postdepositional deformation may disrupt the continuity of the deposit so that what was originally a continuous basin may now appear as two or more separate occurrences of Cenozoic rocks.

Using gravity data alone, it is not possible to determine a unique solution for the geologic feature producing a gravity anomaly. However, when assumptions can be made concerning the density contrast and (or) one or more boundaries between the distributing body and the surrounding material, it is possible to infer from the gravity data reasonable values for the unknown dimensions. Before a gravity anomaly associated with a single geologic feature can be satisfactorily analyzed, it is necessary to isolate the anomaly from other variations in the earth's gravity field. In reducing the data an effort is made to eliminate the effects of variations in the latitude, and elevation between observation points and for the topography surrounding the points. It is also necessary to isolate the anomaly produced by the geologic feature being considered from other anomalies resulting from other density variations in the materials of the earth. Anomalies of markedly different areal extent can be easily separated, but, if anomalies of similar or unknown areal extent overlap, it becomes difficult or impossible to separate them.

Most of the gravity anomalies considered in this report can be classified into two types. One type is of generally broader areal extent and is produced by lateral density variations within the pre-Cenozoic basement rock. The second type is produced by the density contrast between the Cenozoic deposits and the pre-Cenozoic rocks. Quantitative calculations will be made on only the latter type. These anomalies, because they are smaller in areal extent, can usually be separated from the broader major intrabasement anomalies. There is an indication that minor intrabasement anomalies are associated with the structurally low areas in which the Cenozoic rocks occur. The gravity gradients over outcrops of the basement complex adjacent to some of the important accumulations of Cenozoic rocks are increasing away from the areas of Cenozoic rocks slightly more steeply than can be accounted for by the presence of the adjacent Cenozoic rocks. Thus, in some areas there seems to be an intrabasement anomaly with approximately the same areal extent as the anomaly produced by the accumulation of Cenozoic rocks. As it is impossible to separate the gravity effects of the two influences, it is assumed that the intrabasement anomaly is much smaller in amplitude than the anomaly produced by the density contrast between the basement complex and the Cenozoic rocks, and for interpretation the total anomaly is attributed to the Cenozoic rocks.

The densities of samples of the major rock types found in the region were determined. For several reasons these densities are significant only as an indication of the general range in density of the different rock types. Over most of the western Mojave Desert the basement rock is probably weathered to considerable depths, and, while care was taken to collect samples from the less weathered outcrops, it is not known how closely the density determinations made on samples collected from these outcrops indicate the density of the rocks at depths of more than a few hundred feet. Because of the nature of the sampling technique, it is not possible to obtain accurate data on the density of the Tertiary rock. Only the more resistant, and presumably the more dense, Tertiary units occur as unweathered outcrops. The densities determined for samples of these outcrops indicate a density higher than the aggregate density of the Tertiary section. A few density determinations were made on drill cores of the less resistant Tertiary units, but it is not known how closely the observed densities indicate the density of the undisturbed rock at depth. Even if a good approximate determination of the aggregate density of the Tertiary section in one area of Tertiary deposition could be determined, this density determination could not be applied with any degree of certainty to an unknown area.

Figure 23 illustrates the density range of four major rock types indicated by samples collected in the Mojave Desert region. The estimated average density indicated is based on an inspection of the density data and is not the result of any statistical analysis. The density determinations were made on samples selected to indicate the range of the density variations and were not random samples; therefore, the results of any statistical analysis would be misleading.

The densities of the pre-Tertiary rocks range from 2.57 to 3.02 g per cm^3; however, a majority of the pre-Tertiary rocks in the western Mojave Desert are in the density range of 2.65 to 2.70 g per cm^3. The density variations within the pre-Tertiary basement are important, but they would not prohibit making approximate quantitative interpretations of the gravity anomalies produced by the density contrast between the pre-Tertiary and the Cenozoic rocks. The Tertiary rocks, and probably the Quaternary deposits to a lesser extent, are much more evenly distributed throughout the range indicated in figure 23. The densities of the Cenozoic

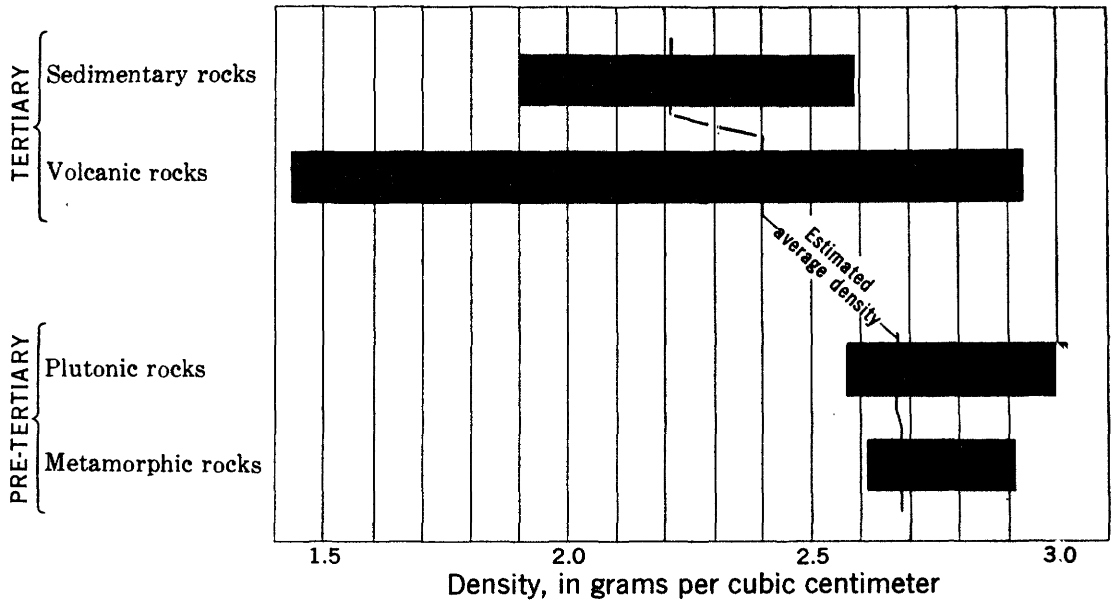

FIGURE 23.—Density range of the major rock types in the western Mojave Desert.

sedimentary rocks are determined by the density of the mineral matter making up the rock and to a very important extent by the amount of induration of the rock. The amount of sorting is also important, at least for the poorly indurated near-surface rocks. Large density variations occur between basins of Cenozoic deposits and even within an individual basin. The data indicate that, in the area of this survey, if no direct evidence is available an assumption that a density contrast of 0.4 g per cm^3 exists between the Cenozoic and pre-Cenozoic rocks is reasonable.

The limited evidence available indicates that in most places the density of the fill within a single basin of deposition may vary over wide limits. For example, the coarse poorly sorted material that would be concentrated along the margins of a basin as fanglomerates is more dense than the finer lacustrine sediments deposited in the center or low part of the basin. Also an increase in density resulting from compaction at depth occurs. Thus, a gravity anomaly can be produced by density variations entirely within the basin fill. Although in some places a simple increase in density with depth can be handled quantitatively, with the amount of subsurface geologic information available in the western Mojave Desert the gravity anomalies produced by the lateral density variations are difficult, if not impossible, to separate from the anomalies produced by the density contrast between the Cenozoic fill and the basement rock. The interpretation of the gravity anomalies in the western Mojave Desert has been further complicated by the migration and deformation of the areas of deposition throughout much of Cenozoic time, producing a complicated horizontal and vertical density distribution within the basin fill.

The problems that are imposed by density variations similar to those described can make it impossible to make an accurate quantitative interpretation of the gravity data. The density variations can be particularly troublesome in interpreting the gravity data in the vicinity of a frontal fault that was active during the deposition of the basin fill. If the faulting followed earlier deposition over a more extensive area, the lateral density variations may not be an important consideration. Each individual gravity anomaly must be considered separately. All available geologic information must be considered in determining how much significance should be placed on the various characteristics of the gravity anomaly and how much and what type of quantitative interpretation is justified.

Once an anomaly has been isolated, the interpretation procedure involves determining a geometric form for the disturbing body that is geologically reasonable, and then, by varying the dimensions and density of the body, obtaining a theoretical anomaly that matches the form and amplitude of the observed anomaly. In considering the negative anomalies associated with Cenozoic fill in the Mojave Desert, it can be assumed that the material producing the anomaly extends to the surface. Thus, one boundary of the disturbing body is always known. The density contrast may vary within a limited range, but any solution that requires a density contrast outside this range can be rejected as being geologically unreasonable. Calculation of the gravity effect of three-dimensional forms is often difficult; however, if one horizontal dimension of the form is several times longer than the other, the calculations can be greatly simplified by assuming that this long dimension is infinite. Then a cross section normal to the long dimension and not near the ends can be treated as a two-dimensional form. Such an analysis is particularly useful in the interpretation of gravity anomalies associated with many fault structures.

In a simple-step or sloping-step structure such as a fault, the magnitude of the total gravity effect is dependent upon the density contrast between the two materials in contact at the step and the height of the step but is independent of the form of the step or depth of burial. The form of the anomaly is dependent upon the form of the step and depth of burial but independent of the density contrast. If an observed anomaly is produced by a single step fault and there are no other features influencing the anomaly, it would be possible to determine the configuration of the fault from the gravity data. In practice, however, this is often not possible.

The general procedure followed in interpreting these data was to collect all available control information and, within the limits imposed by the available control, construct a geologically reasonable subsurface configuration that would produce the amplitude and general form of the observed anomaly. Profiles have been taken across the major anomalies that seem to be amenable to two-dimensional quantitative interpretation. An attempt was made to select the profiles normal to the long dimension of the anomaly and at positions where the gravity relief is greatest and where a maximum of gravity and geologic control is available. The assumption was then made that the gravity anomaly and geologic features have an infinite extent normal to the profile. The error introduced by making this assumption is not prohibitive in view of the other uncertainties involved. Any regional gravity gradient that was apparent was removed and a two-dimensional graticule (Dobrin, 1952 p. 96–99) was used to determine a geologic configuration that would produce a gravity anomaly that would approximate the observed anomaly. Unless otherwise stated, a density contrast between the Cenozoic and pre-Cenozoic rocks of 0.4 g per cm^3 has been used.

It is unlikely that the aggregate density of any of the large masses of Cenozoic rocks in the western Mojave Desert is less than about 2.0 g per cm^3. Therefore, the maximum Cenozoic-pre-Cenozoic density contrast is about 0.7 g per cm^3. Large masses of Cenozoic rock with densities approaching that of the pre-Cenozoic rocks are known to exist in the region. Thus, the minimum density contrast that might be encountered approaches 0.0. Figure 24 illustrates the manner

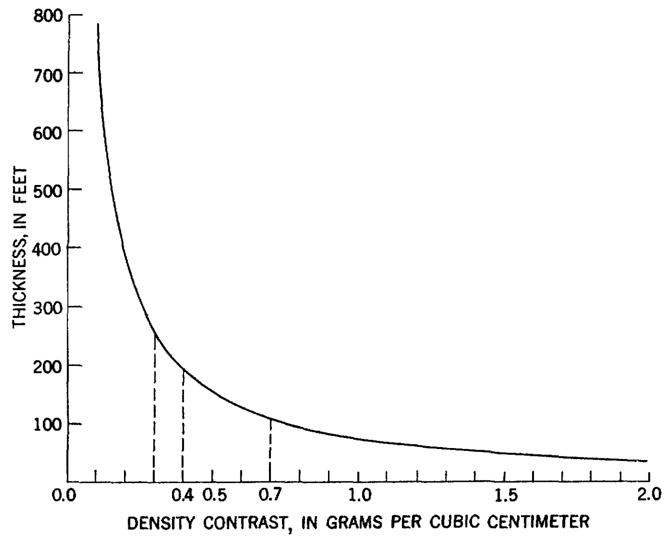

FIGURE 24.—Graph showing relation between the density contrast and the thickness of a layer of infinite horizontal extent required to produce a 1-milligal anomaly.

in which the thickness of an infinite slab necessary to produce a 1-milligal anomaly is dependent upon the density contrast. It is apparent that, if a density contrast of 0.4 g per cm^3 is assumed in the depth estimate and the actual contrast is 0.7 g per cm^3, the actual depth will be about 55 percent of the estimated depth. However, as the density contrast approaches 0.0 the percent error increases rapidly. For the western Mojave Desert the actual depth is probably not less than 55 percent of the depth computed, using a density contrast of 0.4 g per cm^3; however, the actual depth may be several hundred percent greater than the computed depth.

GRAVITY ANOMALIES

GARLOCK FAULT ZONE

From its intersection with the San Andreas fault near Gorman, the Garlock fault zone crosses the southern end of the Tehachapi Mountains to Tehachapi Pass northwest of the town of Mojave, and then follows the southeastern base of the Sierra Nevada to Cantil Valley. At the southwest end of Cantil Valley the principal fault branch diverges from the mountain front and continues into Cantil Valley where the surface expression disappears. Northwest of Cantil Valley two roughly parallel major faults are recognized as part of the Garlock fault zone. The El Paso fault is at the base of the El Paso Mountains and the Garlock fault is located about 1 mile to the south in Cantil Valley. The two faults converge into a single fault to the northeast, which continues to the northeast into the southern end of Searles Lake basin.

Gravity coverage was not obtained over the western end of the Garlock fault where it is within the Teha-

528174—60——3

chapi Mountains. On the segment of the Garlock fault zone along the southeastern base of the Sierra Nevada it was practical to obtain gravity observations along only one line across the fault zone, and this line was at a relatively low angle to the fault zone. The data show a gravity low southeast of, and trending parallel to, the fault zone. A profile across the gravity low is illustrated in figure 25. The profile shows a gravity relief of about 20 milligals and 2 areas of low closure. There is a moderate regional gradient apparent across the anomaly, along which anomaly values decrease northwestward toward the Sierra Nevada.

An analysis of the gravity profile, as shown in figure 25, indicates that about 4,000 feet of Cenozoic rocks is in contact with the plutonic rock along the Garlock fault. The meager gravity data near the contact indicate a near-vertical feature. Southeastward from the Garlock fault the surface of the basement complex is nearly level or rises gradually over a distance of about 7 miles toward the southeast. About 7 miles from the Garlock fault is a local depression, about 2½ miles wide and 6 miles long, elongated approximately parallel to the Garlock fault zone. The floor of depression is estimated to be about 1,000 to 2,000 feet below the projected level of the basement surface. The spacing of the gravity stations does not permit any positive conclusions of the configuration of the depression. However, the gravity gradient along the southeast margin seems to indicate the presence of a fault parallel to the Garlock fault. The depression is probably a graben-type structure developed between faults parallel to the Garlock fault zone. The local depression seems to be related to a locality that is a relatively good producer of ground water.

The major gravity low northeast of Tehachapi Pass is bounded on the north by an east-trending high gravity area. The gravity data indicate a buried ridge of pre-Tertiary rock extending from the Sierra Nevada to the southwest end of the Rand Mountains. The existence of this ridge is confirmed by a drill hole (pl. 10) bottomed at 390 feet in crystalline rock (Dibblee, written communication, 1957).

In the area where the buried ridge of pre-Tertiary rock joins onto the Sierra Nevada, the Sierra Nevada front swings northward from the trend of the Garlock fault zone. The surface trace of a major branch of the Garlock fault extends into Cantil Valley for a distance of about 5 miles. The gravity data indicate that this fault continues on through Cantil Valley with the northwest side displaced relatively downward. This major branch of the Garlock fault zone is referred to in this report as the Cantil Valley fault.

Along the northwest side of Cantil Valley, two major parallel faults, the El Paso and the Garlock, have been mapped from surface evidence. Both faults have gravity expression indicating movement down on the southeast side.

Cantil Valley is a closed basin between the Rand Mountains on the southeast and the El Paso Mountains on the northwest. The basin is about 25 miles long and about 6 miles wide. Toward the northeast the basin floor rises gradually to a low pass north of Randsburg. Toward the southwest the basin opens into the Mojave Desert. Near the center of the basin is Koehn Lake. Commercial salt, gypsum, and ulexite have been produced from the deposits in or around this lake.

The El Paso Mountains rise abruptly to altitudes as much as 3,000 feet above the basin floor. The southeast side of the range is characterized by steep V-shaped canyons and slightly rounded peaks and ridges representing mature stages of erosion. The core of the range is made up of metamorphic and granitic rocks. On the northeastern part of the range 35,000

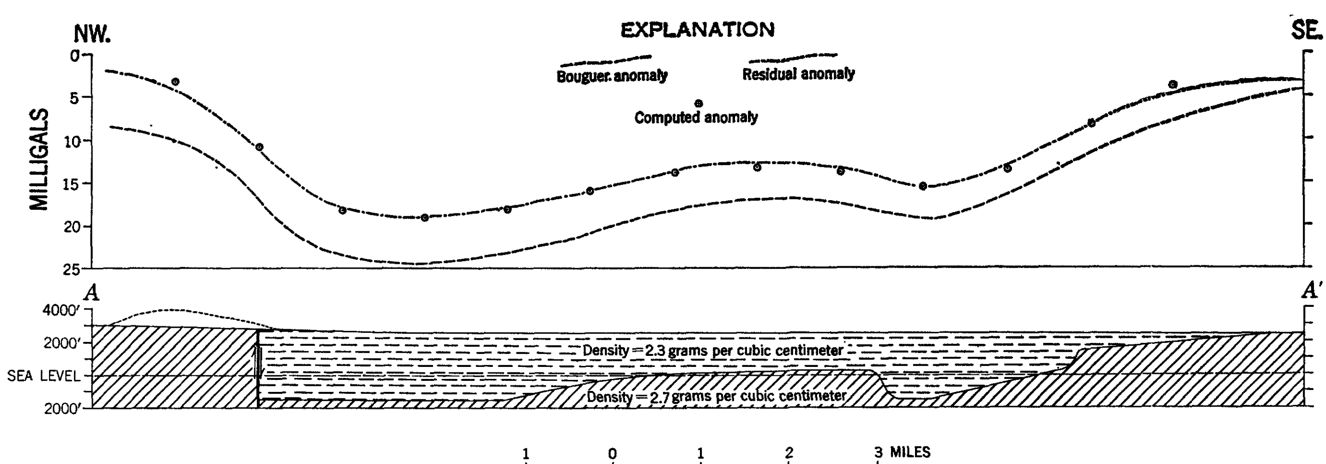

FIGURE 25.—Profile *A–A'*, shown on plate 10, across gravity anomaly southeast of the Garlock fault northeast of Tehachapi Pass.

feet of the Garlock series (Dibblee, 1952, p. 15) is exposed. The Garlock series is slightly metamorphosed sedimentary and volcanics rocks in part, if not all, of Permian age. Cenozoic rocks occur along the northwestern flanks of the range (Dibblee, 1952, p. 25).

The Rand Mountains rise rather abruptly from Cantil Valley to a maximum altitude of about 3,000 feet above the basin floor. To the southeast the range slopes gently into the Mojave Desert. The mountains are composed of granitic and Precambrian(?) metamorphic rocks; the granitic rocks predominate in the southwest and the metamorphic rocks in the northeast.

The El Paso fault lies along the southeast base of the El Paso Mountains. Dibblee (1952, p. 37) states that there is no evidence of recent lateral movement along the fault, and that the movement has been for the most part, if not entirely, vertical. He estimates the maximum vertical displacement is about 10,000 feet. Near the northeast end of Cantil Valley the El Paso fault joins the Garlock fault. The El Paso fault apparently dies out to the southwest.

The Garlock fault was originally studied near the town of Garlock in Cantil Valley where there is evidence of recent left-lateral movement (Hess, 1910, p. 25–26). Northeast of the junction of the El Paso and Garlock faults, the Garlock fault lies along the base of the El Paso Mountains. Southeast of this junction the Garlock diverges from the mountain front. A graben about 1 mile long, a quarter of a mile wide, and more than 50 feet deep lies between the El Paso and Garlock faults just southwest of their junction. Southwest of this graben, except in the vicinity of Garlock, the trace of the Garlock fault is concealed by a cover of alluvium; however, the location of the fault can be inferred from surface evidence. South of Jawbone Canyon the Garlock fault appears to swing to the south along the front of the Sierra Nevada and join the branch of fault zone that lines along the front of the Sierra Nevada northeast of Tehachapi Pass.

Dibblee suggests that a buried fault may exist at the base of the Rand Mountains. There is, however, only indirect surface evidence to back up this possibility.

A series of piedmont alluvial fans extend into Cantil Valley from both sides. The alluvial deposits are underlain by continental sediments of the Ricardo formation (Pliocene to Pleistocene) (Dibblee, 1952, p. 29–30). Northwest of Cantil and near Garlock the Ricardo formation is exposed between the Garlock and El Paso faults. Several oil test wells have been drilled near Cantil to depths ranging from 1,859 to 5,065 feet (Dibblee, written communication, 1958). All the wells were bottomed in continental Tertiary sedimentary rocks.

The gravity low in Cantil Valley has the greatest relief of any local anomaly in the western Mojave Desert. The low is about 27 miles long, 6 miles wide, and its minimum lies about 1 mile southeast of Saltdale. The long axis parallels the Garlock fault zone.

A profile across Cantil Valley is illustrated in figure 26. Along this profile there is a gravity relief of about 43 milligals. The gravity gradient (15 mgal per mile) in the southeastern part of the profile is the steepest mapped in the western Mojave Desert. A regional gradient across the valley is evident on the profile and is partly responsible for the steep gradient. The regional gradient is probably part of a major crustal gravity anomaly associated with the Sierra Nevada. To facilitate the interpretation along the gravity profile, an assumed regional gradient of about 2 milligals per mile was removed.

The character and position of the gravity minimum within 1 mile of the Garlock fault indicate a mass deficiency just south of the Garlock fault. The gravity minimum could result from either a dip of the basement-rock surface toward the Garlock fault from the southeast or an accumulation of unusually light sediments near the surface just southeast of the fault. The general position of the low can be accounted for by a slope of the basement-rock surface; however, the sharpness of the gravity minimum indicates a near-surface effect, such as an accumulation of lighter sediments under the present playa. Both a sloping basement-rock surface and an accumulation of less dense sediments were assumed to construct the profile shown in figure 26.

An analysis of the gravity profile indicates that the vertical displacement along the northwest side of the gravity minimum did not occur entirely at the El Paso fault. Much of the vertical displacement occurred southeast of the El Paso fault, probably at the Garlock fault but perhaps at other parallel faults. In figure 26 the displacement has been attributed to vertical movement at only the El Paso and Garlock faults.

Along the southeast side of Cantil Valley the steepest gravity gradient occurs out in the valley over a mile removed from the surface contact between basement rock and the alluvium. The conclusion is drawn from this part of the gravity profile that there is no major fault along the contact between the surface basement rock and the alluvium, but that the concealed Cantil Valley fault with considerable vertical displacement is within the valley.

If the indicated position for the Cantil Valley fault on the profile is extended to the southwest along the steep part of the gravity gradient, it will join the segiment mapped from surface evidence in the southwest corner of the valley. Extended northeast from

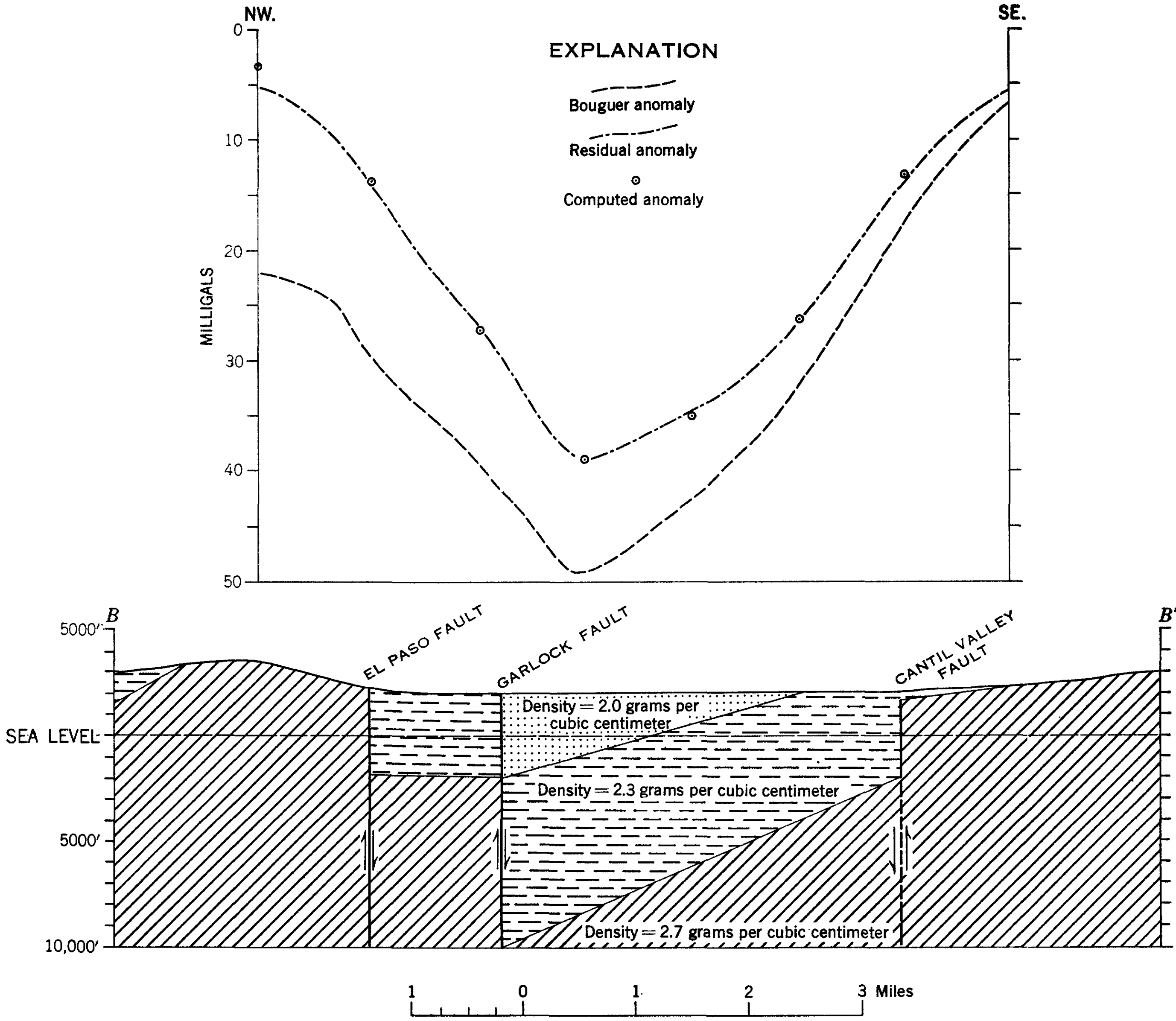

FIGURE 26.—Profile *B–B'*, shown on plate 10, across Cantil Valley.

the profile the indicated position of the fault will coincide with the position of the two springs indicated on the map (pl. 10) and will lie southeast of a fault in the northeast end of Cantil Valley located by Dibblee on the basis of surface evidence (Dibblee, 1957).

The major features contributing to the gravity anomaly in Cantil Valley are large and occur in a small area; therefore, their gravity effects overlap to an important degree, and it is impossible to isolate the effects of the different features. Also, the regional gradient is large and is not well understood. Thus, the ambiguities involved in the interpretation of this anomaly are greater than those involved in the other less complex anomalies in the region. However, the major features of Cantil Valley can be inferred from the gravity data, though the details may vary considerably from the cross section of figure 26.

Cantil Valley seems to be a deep graben within the Garlock fault zone. On the northwest the graben is bounded by the El Paso and Garlock faults, and the vertical displacement is distributed between them and perhaps other parallel faults lying between them. The floor of the graben probably slopes downward toward the Garlock fault and the greatest thickness of Cenozoic deposits occurring just south of the Garlock fault. The Cantil Valley fault forms the southeastern boundary of the graben. The thickness of the Cenozoic deposits in the graben is about 2 miles. Large lateral variations in the density of the Cenozoic deposits probably occur so that fine, less dense lake sediments are in the structurally low part of the graben and coarser, more dense materials toward the edges.

The gravity gradient indicates that the fill thickens rapidly to the east away from the Sierra Nevada at the southwest end of the graben. At the southwest end of Cantil Valley near the mouth of Jawbone Canyon, the Garlock fault zone is intersected at nearly a right angle by the fault along the east front of the Sierra Nevada. There is no gravity expression of this fault apparent, though exposures of the fault on both sides of the canyon show Tertiary rocks on the east in fault contact with plutonic rock on the west. The absence of any gravity expression of this fault in Jawbone Canyon indicates that there is not a thick concealed Tertiary section just east of the fault.

RANDSBURG-HARPER LAKE AREA

Because of the lack of access roads over the Rand Mountains, it was only possible to complete one traverse over the range near the northeast end. However, the data collected clearly indicate the existence of a gravity high, though the magnitude may be considerably greater than is indicated on the contour map.

The area south of the Rand Mountains is typical of the western Mojave Desert. Isolated hills rise above the gently sloping alluvial-covered plain. To the east the northwest-trending Fremont Peak range is one of the most prominent topographic features in the area surveyed. Although the gravity data over the Fremont Peak range are not complete, a gravity high appears to coincide with the range. A gravity high extends from the northern end of the Fremont Peak range to the Rand Mountains. This high corresponds approximately to a topographic high, and probably represents a partly buried basement ridge.

Northeast of Fremont Peak and south of Cuddeback Lake there is a strong northwest-striking gravity gradient which seems to be associated with the Harper fault zone. The gravity gradient indicates that the fault zone extends to the northwest for several miles from the location where the recognized surface expression terminates. Although recent movement along this fault zone has been right lateral and relatively down on the southwest, the gravity gradient indicates that south of Cuddeback Lake there has been an overall relative downward displacement of the northeast block of about 7,000 feet.

Northwest of Barstow a gravity low is associated with the Barstow syncline. The Harper fault zone transects the western end of the Barstow syncline and there is suggestive gravity evidence indicating that the right-lateral movement along this fault zone may have offset the axis of the syncline. In the vicinity of Harper Lake the gravity data indicate that a thin accumulation of Cenozoic deposits covers a basement-complex surface of moderate relief. Drilling has revealed that the surface of the basement complex is generally within 1,200 feet of the surface. At the northwest end of Harper Lake there is a gravity low indicating a local depression.

North of Hinkley the east-striking gravity feature with a strong gradient decreasing northward is difficult to explain. A major part of the feature occurs over an area where the basement complex crops out. The line of gravity stations crossing the feature north of Hinkley passes between two outcrops of quartz monzonite. Perhaps there is a considerable depth of fill between these outcrops with the result that the contours based on these stations do not reflect the true anomaly pattern in the area. More detailed gravity observations in the Harper Lake area would probably serve to define gravity anomalies associated with several important geologic features that are not indicated by the data now available.

Southwest of the gravity ridge between the Fremont Peak range and the Rand Mountains and trending parallel to it is a major gravity low with a closure of about 15 milligals. The low is bounded on the southwest by the Lockhart fault. Along the northeast edge of the gravity low, the gravity contour lines trend parallel to a branch of the Lockhart fault. One deep hole has been drilled in the area of the low. The depth is reported to be 1,750 feet; it did not penetrate basement rock (Gale, 1946, p. 373–374).

A profile across the anomaly is illustrated in figure 27. The gravity minimum lies within about 1 mile

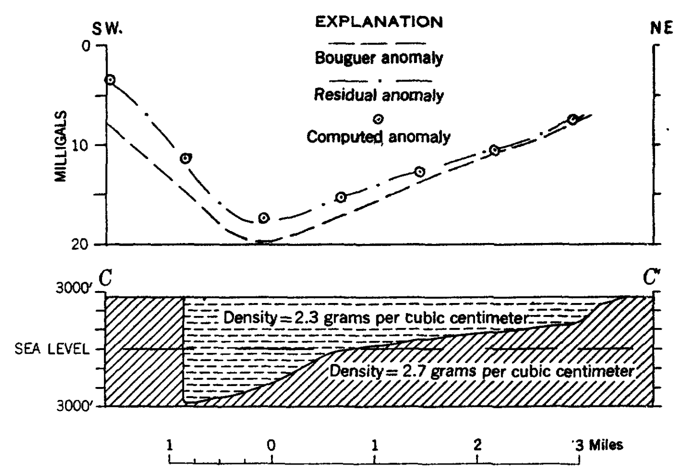

FIGURE 27.—Profile C′-C′, shown on plate 10, across gravity anomaly south of the Rand Mountains.

of the Lockhart fault and the northeast edge of a basement outcrop. It seems probable that the greater thickening of the Cenozoic deposits along the southwest edge of the gravity low occurs along the Lockhart fault, and that this fault is nearly vertical. There is a slight steepening of the gravity gradient in the general area where a projection of the north branch of the Lockhart fault crosses the profile. The steepening may indicate that the branch extends to the northwest and has a vertical component of displacement.

BORON-KRAMER JUNCTION AREA

Just north of the town of Boron in the central part of the surveyed area is the Kramer borate district. For about 30 years this district has been the world's leading source of borate minerals (Gale, 1946, p. 329; Mumford, 1954, p. 20–22).

Borate minerals occur in a mineralized area roughly 4 miles long and 1 mile wide. The deposit occurs in a fine-grained colloidal-type shale of Tertiary age apparently laid down in standing water. The lake beds are underlain by a basalt flow which in turn is underlain by several hundred feet of sedimentary and pyroclastic rocks. The sodium borate body, chiefly tincal ($Na_2B_4O_7 \cdot 10H_2O$) and kernite ($Na_2B_4O_7 \cdot 4H_2O$), lies at depths of from 300 to 1,000 feet below the surface. The deposit contains impurities of clay and other insoluble materials, but the massive borate deposit does not contain appreciable amounts of other soluble material. Colemanite ($C_2B_6O_{11} \cdot 5H_2O$) and ulexite ($NaCaB_5O_9 \cdot 8H_2O$) occur in the clay and shale that surround the sodium borate body. Quaternary alluvium completely covers the surface over the borate deposit, and no surface indication of the rich deposit has been recognized.

The Kramer ore body lies along the south edge of a gravity low (pl. 11). The gravity minimum is about 2 miles north of the borate body. South of the borate body is a steep gravity gradient, striking parallel to the long axis of the borate body, which probably marks the position of the fault near the Western Borax mine postulated by Gale (1946, p. 341). From the gravity data it is estimated that the fault is located in the approximate position indicated on the geologic map and that at present the surface of the basement is displaced along this fault relatively down to the north from 1,500 to 2,000 feet. The borate-bearing lake beds were probably deposited in a small local basin bounded on the south by this east-trending fault that was active during the period of deposition.

No reliable drill-hole report has indicated the depth of the basement rock in the area of the gravity low in which the Kramer deposit is located. The extent and thickness of the several basalt flows that occur in the Tertiary section are not known; it is not possible, therefore, to evaluate the effect the dense basalt has on the gravity anomaly. There is a possibility that the basalt has an important gravity effect and is displacing the position of the gravity minimum. However, as there is no definite evidence to support this possibility, it is assumed that the position of the gravity minimum indicates the location of the thickest Cenozoic section. If this is the actual condition, then the borate deposit does not occur in the area of the thickest Cenozoic section.

The gravity low centered about 6 miles west of Boron is connected with the low associated with the Kramer deposit. The low west of Boron has a northwest trend and is bounded on the southwest by a gravity gradient that probably marks the trace of a northwest-trending fault. No surface indication of this fault has been recognized. The results of recent drilling for the U.S. Geological Survey in the southern part of the area of the low indicate that there is present a Cenozoic section containing over 2,328 feet of alluvial sands and silts (Benda and others, 1960).

A high-gravity trend extends from the pre-Tertiary outcrops north of Boron to those east of Kramer Junction. This high-gravity trend suggests that the alluviated valley area between these exposures of pre-Tertiary rock is underlain by pre-Tertiary rock at shallow depths. Another gravity low north of Kramer Junction is connected to the low associated with the Kramer deposit. The gravity trend along the southwest margin of this low probably is produced by a northwest-trending fault. Drilling for the U.S. Geological Survey has confirmed the existence of at least 3,500 feet of Cenozoic fill containing some layers of Colemanite (Benda and others, 1960). An isolated gravity low lies south of Kramer Junction. A single hole drilled for the U.S. Geological Survey near the center of this anomaly penetrated through 3,500 feet of conglomerate and sandstone (Benda and others, 1960).

BARSTOW-CAJON PASS AREA

The Kramer Hills, Iron Mountain, and the Shadow Mountains have only moderate topographic relief. Each of the ranges has a core of pre-Tertiary basement rocks. Several thousand feet of Tertiary strata crop out in the Kramer Hills, but no Tertiary rocks have been recognized in the vicinities of the Shadow Mountains nor Iron Mountain. Gravity highs are associated with each of the three topographic features; however, the gravity highs generally are more extensive than the topographic highs.

Between the Kramer Hills and Iron Mountain is a north-trending gravity trough having a relief of more than 20 milligals. The anomaly is bounded on the east by a steep gravity gradient. This steep gradient may be interpreted to indicate a fault which is the eastern boundary of a trough containing about 5,000 feet of Cenozoic deposits (fig. 28). An oil-test hole drilled in the northwestern part of this low struck basement rock at 2,640 feet (Bowen, 1954, p. 182). The depth to basement reported in this hole is consistent with the depths shown on the profile in figure 28. The gravity gradient continues northward to the Lockhart fault and southward to the area where the Helendale fault enters the surveyed area. Indirect surface evidence indicates that the Lockhart fault or a branch of it extends southeastward toward Hinkley Valley (Dibblee, oral communication, 1957), such an extension is not inconsistent with the gravity data though no great vertical displacement is indicated. The fault inferred from the steep gravity gradient along the east side of the gravity low is probably continuous with the Lockhart fault and may also be related to the Helendale fault.

Northeast of the Shadow Mountains and south of the Kramer Hills is an east-trending gravity low that joins the low east of the Kramer Hills. At the western end of the low is a moderate gravity gradient trending a little east of north. South of the low is a rather steep gravity gradient that forms an arc around the basement highland associated with the Shadow Mountains.

North of the axis of this low an oil test was drilled to 4,130 feet without reaching basement rock (Dibblee, written communication, 1957). The hole reportedly bottomed in a granite cobble conglomerate and sandstone, which may be near the base of the fill. However, this well did not penetrate, and possibly did not reach, the 1,000-foot section of Tertiary volcanic flows and lake beds that overlies the basement complex in the Kramer Hills 4 miles north, and therefore may have been bottomed more than 1,000 feet above the basement complex. If a density contrast of 0.4 g per cm^3 is assumed in interpreting this anomaly (fig 29), the bottom of this hole would seem to be near the basement complex and the depth of the basement complex near the axis of the gravity low would be about 4,500 feet. The surface of the basement complex rises toward the Kramer Hills and the Shadow Mountains, but there is no definite indication in the gravity data of a fault adjacent to either of these topographic features. The west end of the gravity low is a steep gravity gradient striking a little east of north. The gradient approximately coincides with the western limit of the outcrops in this area, and may be produced by a fault of considerable vertical displacement.

The gravity low south and southwest of Barstow may indicate a westward extension of the Daggett basin, which has been mapped to the east of Barstow.

Between Victorville and Cajon Pass the north-sloping surface is underlain by fanglomerate and alluvium of Quaternary age deposited as part of a large

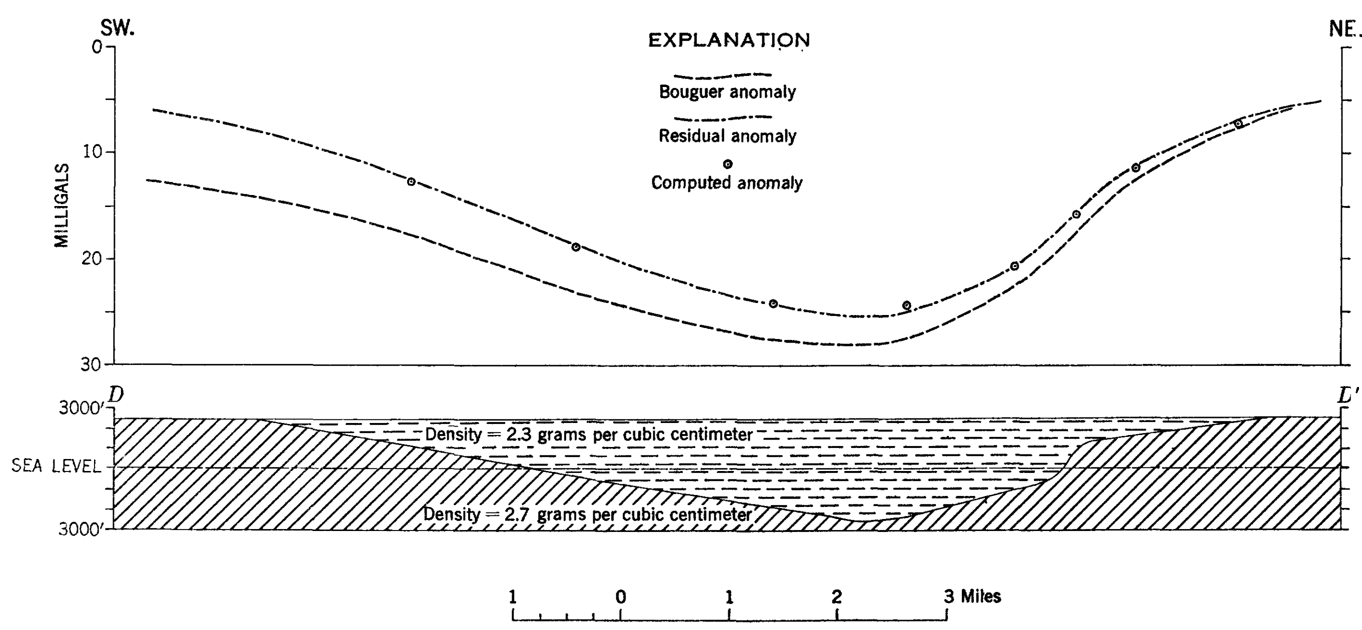

FIGURE 28.—Profile *D–D'*, shown on plate 10, across gravity anomaly west of Iron Mountain.

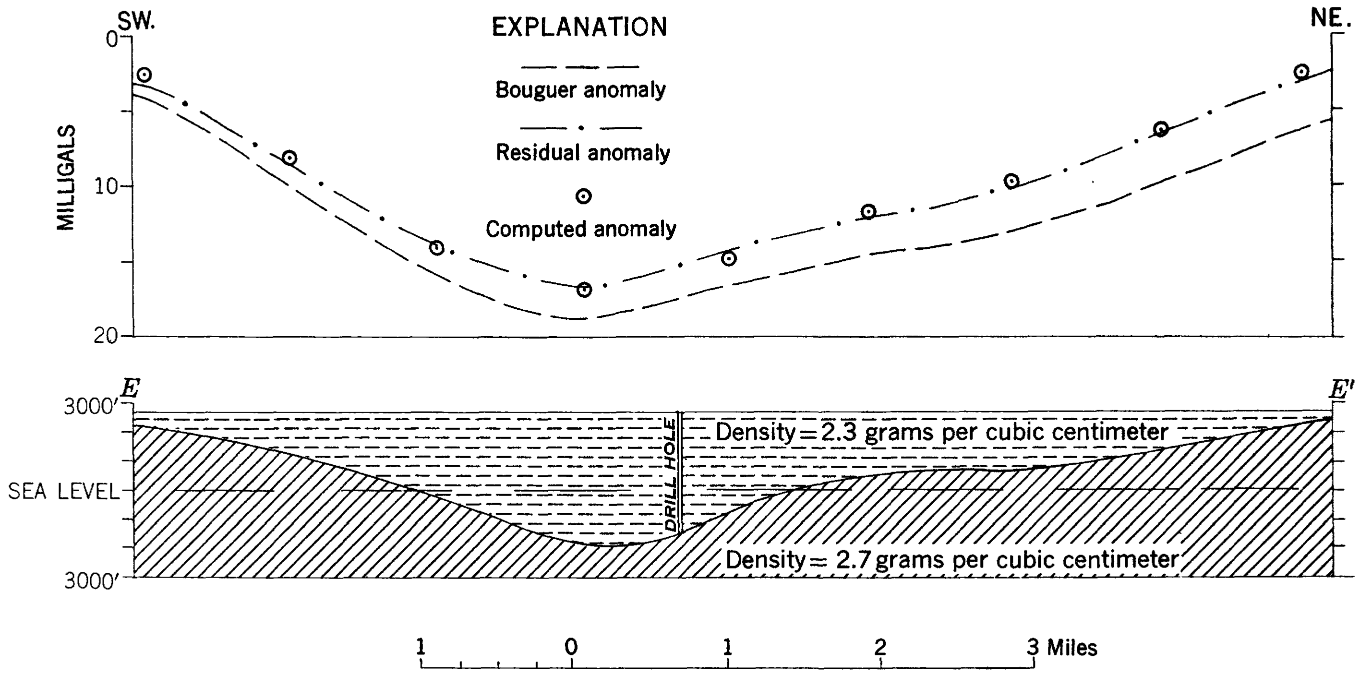

FIGURE 29.—Profile *E–E'*, shown on plate 10, across gravity anomaly south of the Kramer Hills.

alluvial fan that once extended northward from the San Bernardino and San Gabriel Mountains. Headward erosion of Cajon Creek has captured most of the drainage that deposited the fan. In the Cajon Pass area more than 6,000 feet of Cenozoic stream-laid deposits is exposed; these deposits dip generally northward under this large alluvial fan.

North of Cajon Pass is an extensive gravity low area with four low closures. The main part of the anomaly, which contains three of the four recognized low closures, trends easterly. The western end of the anomaly swings to the north and continues with diminished amplitude into the area of Mirage Lake. In Cajon Valley along the southwest margin of the anomaly there is a steep northwest-striking gravity gradient. The strike of the gradient is parallel to the Cajon Valley fault (Noble, 1954b, pl. 5), but the steepest part of the gradient is about 1 mile to the northeast of the indicated surface position of the fault. The gradient indicates that the depth to the top of the basement complex increased rapidly to the northeast from the indicated position of the Cajon Valley fault, perhaps along steep faults parallel to the Cajon Valley fault. An oil test about 1 mile northeast of the indicated position of the fault was drilled to 5,800 feet without reaching the basement complex (Dibblee, written communication, 1956).

Between Adelanto and Victorville there is a north-northeast-trending gravity minimum, in part separated from the main body of the low by a gravity high extending southwest from Victorville. No deep holes have been reported in the area of this low, but it probably marks a deep local depression. A well southwest of Adelanto is reported to have been drilled in crystalline limestone, schist, and granite from 1,350 feet to 3,216 feet (Bowen, 1954, p. 183). This drill hole is on a gravity high that extends southward from Shadow Mountains. As the intrabasement anomalies in the region north of Cajon Pass are so poorly understood, no quantitative interpretation of the gravity anomaly has been attempted. Unless there are large lateral density variations within the Cenazoic section, the greatest depth to the basement complex occurs near the gravity minimum and is about 10,000 feet.

Along the San Andreas fault zone the gravity contour lines trend generally parallel to the fault zone; however, no significant local gravity anomalies associated with the fault zone were recognized from the gravity data collected. More detailed coverage would indicate numerous gravity anomalies associated with local features along the fault zone.

The gravity data indicate that a basement high extends across the east end of Antelope Valley from Pearland to Lovejoy Buttes. The irregularity of the gravity contour lines in the Lovejoy Buttes-Black Butte area probably indicate intrabasement effects plus buried basement topography.

ANTELOPE VALLEY AREA

Antelope Valley is a broad nearly level alluvium-floored valley in which a few outcrops of Tertiary and pre-Tertiary rocks rise above the alluviated surface. The gravity high trend which extends southwesterly from Lovejoy Buttes to the San Andreas fault is flanked on the northwest by a major closed gravity low which extends northeastward from Lancaster to the south end of Rogers Lake. An oil-test hole on the northwest flank of this gravity low was drilled through Cenozoic continental deposits to bottom at 5,560 feet (Dibblee, written communication, 1955). A profile across the anomaly through the drill hole is illustrated in figure 30. The existence of 5,560 feet of Cenozoic fill at the drill-hole location on Rosamond Lake would not have been inferred from the gravity anomaly, using a density contrast of 0.4 g per cm^3. If the assumption is made that the basement surface is at least 5,560 feet deep at the point indicated on the profile and that there is a single density contrast of 0.3 g per cm^3 between the Cenozoic deposits and the basement rock, the observed anomaly can be accredited to the basement-surface profile illustrated in figure 30. The maximum depth to basement rock would then be 10,000 feet in the vicinity of the gravity minimum. The interpretation along this profile may be complicated by intrabasement anomalies that cannot be identified and possibly by lateral density variations within the Cenozoic section.

The gravity high centered over the pre-Tertiary exposures north of Rosamond Lake extends southwesterly across Antelope Valley to the San Andreas fault with a shallow gravity saddle midway between Rosamond and the San Andreas fault. Northwest of this gravity saddle there is a minor gravity low which probably indicates a local subsidence. In the western part of this low there is an outcrop of tuff of Tertiary age dipping eastward about 30°.

In the western end of Antelope Valley there is an extensive gravity low. The main body of the anomaly is bounded on the south by a steep east trending gradient. Along the northwestern part of the anomaly the gradient is more gentle and trends parallel to the Garlock fault and the front of the Tehachapi Mountains. A branch of the anomaly extends along the Tehachapi Mountains to the vicinity of Soledad Mountain.

Figure 31 illustrates a profile across the anomaly through Antelope Buttes. The gravity anomaly is not well suited to a two-dimensional analysis; however, such an analysis will indicate some of the important features of the subsurface configuration producing the anomaly. The Tertiary rocks northwest of Antelope Buttes are dipping toward the gravity minimum at angles of 30°–45° (Dibblee, written communication, 1956). An analysis of the gravity gradient indicates that the interface between the basement rock and the Tertiary rocks has a considerably greater dip toward the gravity minimum. It may be that the Tertiary-basement interface dips more steeply than the Tertiary rocks, or perhaps the steep gravity gradient may be produced by a fault. In either case the basement surface rises abruptly along the south and southeast margins of the gravity low.

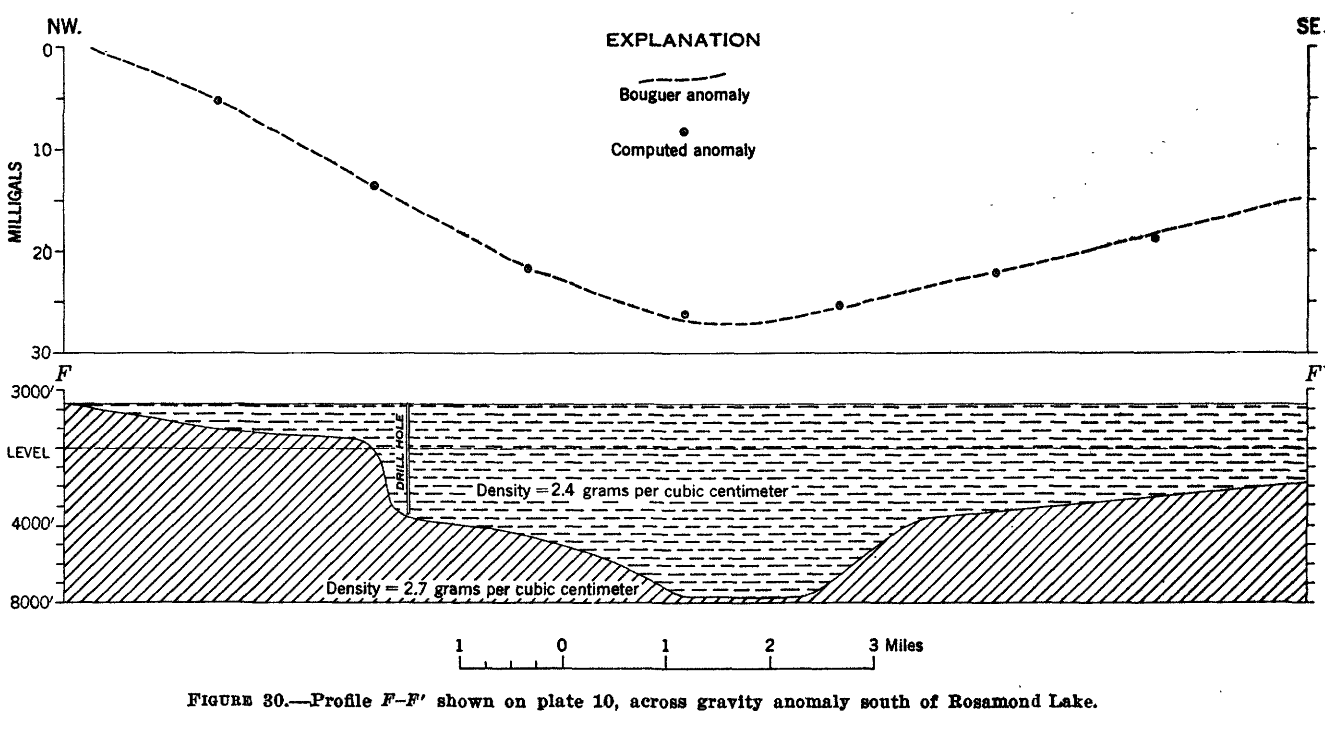

FIGURE 30.—Profile *F–F'* shown on plate 10, across gravity anomaly south of Rosamond Lake.

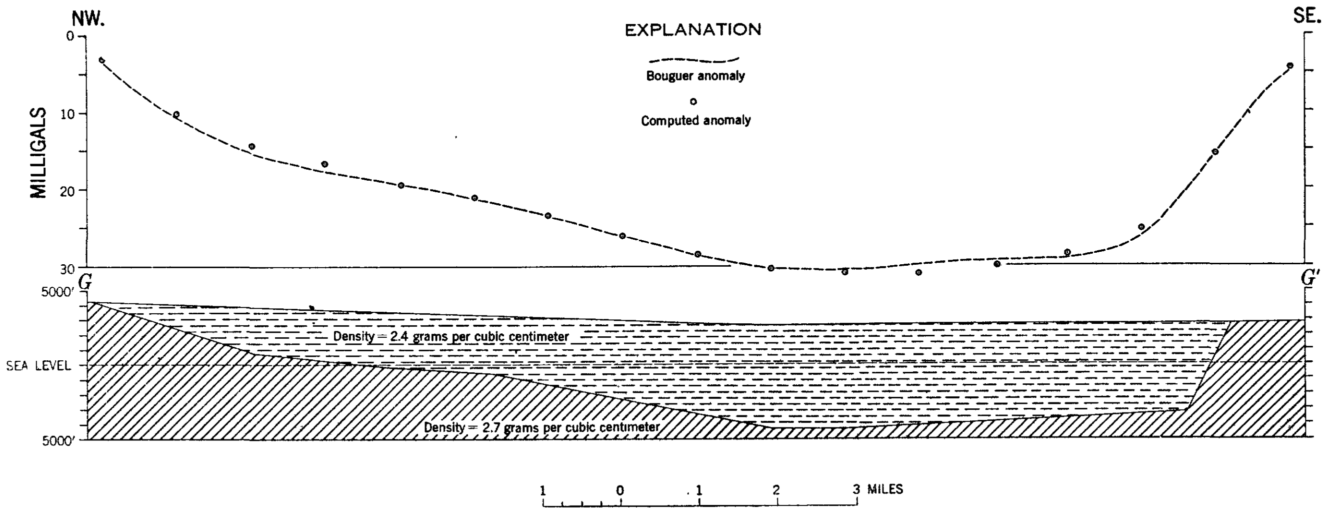

FIGURE 31.—Profile *G–G'*, shown on plate 10, across gravity anomaly in western Antelope Valley.

Northwest of the gravity minimum the anomaly values rise more gently toward the Tehachapi Mountains. There is no evidence in the gravity data of major faulting in this area. An oil-test hole at the west end of this low passed through 4,150 feet of rocks and sediments of Cenozoic age without reaching basement (Wiese, 1950, p. 58). The log of a drill hole 2.7 miles northeast of the profile reported basement rock at 3,300 feet (Oakshott and others, 1950, p. 18). If this hole is projected along a line parallel to the gravity contours, it would cross the profile in figure 31 at a point where a depth to basement of 4,000 feet is indicated. The maximum depth to basement rock indicated along the theoretical profile is 7,000 feet.

Local gravity highs are apparent over Antelope Buttes and Quartz Hill, and there is an indication of possible faulting (down to the south) along the southern margins of both. The overall gravity trend is parallel to the San Andreas fault, but local east-west gravity trends are evident along the southern margin of Antelope Valley.

SIGNIFICANCE OF THE GRAVITY ANOMALIES

GEOLOGIC SIGNIFICANCE

Although sedimentary and volcanic rocks of Paleozoic and possibly Precambrian and Mesozoic age are present, the pre-Tertiary history of the western Mojave Desert is not well understood. In middle or late Mesozoic time enormous volumes of plutonic igneous rock were emplaced. Although one or more late Mesozoic orogenies had considerable effect on the western Mojave region, very little information is available from studies within the region on the nature or date of the orogenic events. The gravity studies have not made a significant contribution to the study of the local pre-Tertiary geology.

During much of early Tertiary time the western Mojave region was rising and the products of erosion were removed from the region. Beginning in middle Miocene and continuing intermittently to present time, local depressions have developed and have been filled with volcanic material and debris derived from adjoining highlands. A middle Pliocene orogeny deformed the earlier Tertiary sedimentary rocks, and local thrust faults developed (Hewett, 1954a).

Hewett (1954a, p. 17), in reporting on the Tertiary basins in the Mojave block states:

> (1) none of Eocene or Oligocene age are yet known; (2) some basins contain thick sections of middle and upper Miocene sediments, but none seem to contain superimposed Pliocene sediments; (3) several basins containing lower Pliocene sediments are known, but none show underlying Miocene sediments or overlying middle Pliocene sediments; and (4) the only middle (lower) Pliocene section is not underlain by older Pliocene or Miocene sediments.
> This situation seems to indicate some shifting of areas of downwarp, with accompanying shifts in basins of deposition.

In the western part of the Mojave block excluding Cantil Valley, the present centers of deposition, as indicated by the location of the major playas, do not occur over the areas of thickest Cenozoic deposits, as revealed by the gravity data. Rogers Lake is centered in an area where the basement complex is near the surface and there is a small basement outcrop in the lake. Rosamond, Harper, Mirage, and Cuddeback Lakes coincide with Cenozoic deposits of considerable thicknesses, but, as indicated by the gravity data, they are all offset from the thickest section of Cenozoic sediments. Debris derived from recently uplifted masses adjoining the Mojave block is altering the drainage pattern along the margins of the Mojave block. However, both the geologic and gravity observations indicate that, since the beginning of Tertiary deposition in the Mojave block, the basins of deposition have been shifting because of deformation within the Mojave block.

Areal mapping within the western Mojave block has revealed several major and numerous minor northwest-trending faults parallel to the San Andreas fault. On some of these faults there is evidence of reversal of vertical displacement, resulting in an apparent scissors-type displacement. This is readily apparent on the Lockhart fault and also on the Harper fault zone. On these faults and on several others there is geologic evidence of right-lateral displacement on a small scale. It seems probable that the relative vertical displacement along these faults and other wrench faults in the region is not only reversed at different places along the lateral extent of the fault, but that the direction of vertical movement may not be persistent at one place. Thus, the vertical displacement apparent at the surface may not indicate the direction of net displacement. Similarly, the direction of net vertical displacement as inferred from the gravity data may not correspond to the direction of the most recent vertical movement. The lack of persistence of the vertical movement along individual faults of this northwest-trending system and other related wrench faults is probably a contributing factor to the migration of areas of deposition throughout late Tertiary and Quaternary time.

The western Mojave Desert lies in a region of profound tectonic activity. To the north and northeast are elongated basins and ranges with striking evidence of recent deformation. To the northwest and southwest are the recently uplifted Sierra Nevada and Transverse Ranges. Surrounded on three sides by regions of great relief and pronounced structural trends, the western Mojave Desert exhibits none of the surface features that distinguish the neighboring regions. The surface of low relief that now characterizes the western Mojave Desert is in marked contrast with the gravity anomaly map that has pronounced local and regional variations and several well-defined local trends.

The gravity lows are no doubt largely an expression of the present dispositions of the major accumulations of Cenozoic rocks with densities appreciably less than the pre-Cenozoic crystalline rocks. The Cenozoic rocks have either been deposited or preserved in areas that have been downwarped or downfaulted during Cenozoic time. Thus, the trends of the gravity anomalies indicate trends of Cenozoic deformation as it is reflected in the relief of the basement-rock surface. It should be kept in mind, however, that major structural features need not have any gravity expression if they do not result in differential movement of rocks with different densities.

The well-defined trends in the topography of the pre-Tertiary rock surface as interpreted from the gravity data are shown on plate 12 along with the faults located on the basis of the areal mapping. For the gravity features in an area north and west of Rogers Lake a trend parallel to the Garlock fault zone is dominant. East and northeast of Rogers Lake the dominant trend for both the features having surface expression and those inferred from the gravity anomalies is northwest. In the Mirage Lake-Victorville area north of Cajon Pass a north-south trend of the gravity features is evident. In a strip northeast of the San Andreas fault several eastward-trending features are indicated by the gravity anomalies. These features make an angle of about 30° with the San Andreas fault zone.

In the region just southeast of the Garlock fault zone the trend of all the major gravity anomalies is parallel to the Garlock fault zone. This is in marked contrast to the fault pattern developed from the areal mapping. As shown on plate 10, only in a part of Rand Mountains and in the hills north of Rosamond are the faults alined parallel to the Garlock fault zone apparent from areal mapping. The gravity anomaly map, however, reveals that nearly all the major features having gravity expression are elongated parallel to the Garlock fault zone. This trend extends as far south as Rosamond Lake and is evident not only in the negative anomalies associated with accumulations of Cenozoic rock but also in the positive anomalies over major basement-rock mass in the Rand Mountains and north of Rosamond Lake.

Most of the important faults located in this region in the areal mapping trend northwest approximately parallel to the San Andreas fault zone. Several of these faults are apparent in alluvium-covered areas; some form the contact between the bedrock and alluvium, indicating recent movement. Nearly all the northeast-trending faults which have been located in the areal mapping occur within the Tertiary or older rocks. This can be interpreted as indicating that an older system of northeast-trending faults along which considerable vertical movement has occurred in Cenozoic time is now relatively quiescent, and the northwest-trending system which is now dominate has not produced major vertical displacement in this region.

In the northeastern part of the surveyed region the trend of the gravity anomalies agrees with the structural trends apparent from the areal mapping. Several of the northwest-trending faults have expression on the gravity anomaly map with considerable vertical displacement indicated for some.

The northerly trend of the gravity anomalies in the Helendale-Victorville area is not well defined and perhaps not particularly important. It is, however, evident that several major gravity anomaly features are not in alinement with the northwest trend which dominates the gravity anomaly map in the region to the north and is also the dominate trend of the surface faults in this region. The only evidence of a northerly trend apparent on the geologic map is a vague trend of the contact between the bedrock and alluvium north and south of Helendale. Until more is learned concerning the nature of the apparently quiescent deformation which resulted in the present gravity pattern, it is difficult to speculate on the causes. It is, however, interesting to note that this anomalous region occurs directly north of Cajon Pass where the San Andreas fault zone crosses the Transverse Ranges between the San Gabriel and San Bernardino Mountains. The easterly trend of several minor gravity anomalies north of the San Andreas fault zone probably is an expression of structure closely related to the fault zone. On the geologic map several faults diverge from the trend of the fault zone with approximately the same trend as the minor gravity anomalies. However, none of the gravity anomalies can be directly correlated with known surface faults.

One area where the gravity data may make an important contribution to the understanding of regional tectonics is in the vicinity of Cantil Valley where the east front of the Sierra Nevada intersects the Garlock fault zone. Here the fault zone consists of 3 major branches between which a subsidence of perhaps 2 miles has occurred. In this area the southwest segment of the fault zone is offset to the south. From Cantil Valley west to the San Andreas fault the trend of the Garlock fault zone is about N. 60° E. From Cantil Valley eastward the strike of the fault becomes more easterly until it becomes approximately east in the vicinity of Leach Lake northeast of the surveyed area. Also, the line Hewett (1954b, p. 17) proposes to draw separating the Mojave block into two parts extends S. 45° E. from the northeast end of Cantil Valley. Of the significance of this line Hewett states (p. 17):

> The area southwest of this line contains many closely spaced faults, most of which trend northwest or roughly parallel to the San Andreas fault * * *. In the few places where the dips of these faults are observable, they are steep * * *. In the places where these faults have been studied, they seem to disregard foliation, joint patterns, and bedding planes in the adjacent rocks * * *.
>
> Within the area that lies northeast of the assumed N. 45° W. line, there are only a few proven faults as far north as the Garlock fault. The trend of these faults is diverse, and evidences of Recent movement are rarely observed.

The deep subsidence, the offset of the Garlock fault zone, and the change in trend of the fault zone are three anomalous conditions which indicate that this area is worthy of further study. Additional geophysical and geologic investigations in adjoining areas, particularly to the north and east, combined with more detailed studies in the Cantil Valley area may yield considerable information on the tectonics of this region.

The break between the Sierra Nevada block and the Basin and Range province may have had a profound effect on the Garlock fault zone east of Sierra Nevada and upon the Mojave block. Other tectonic events outside the western Mojave Desert also probably exerted considerable influence on the region. When the gravity data obtained in the western Mojave Desert are considered along with geologic and geophysical data from adjoining regions, they will probably make a considerable contribution to the understanding of the regional tectonics.

ECONOMIC SIGNIFICANCE

The information on the Cenozoic geology inferred from the gravity data has important significance relative to several economic problems. The gravity data reveal the concealed areal extent of several known basins of Cenozoic sedimentary fill and several basins heretofore unknown, that are completely concealed by Quaternary alluvium. The deposit of borates at the Kramer borate district is in one of the basins of Cenozoic fill. Several of the other basins have been tested or partly tested by deep drilling; others are unexplored.

Noble (1926a, p. 46) has described the discovery of the borate deposit at Boron as follows:

> The discovery of the deposits was purely accidental, for they lie beneath a broad alluvial plain whose featureless surface of sand and gravel affords no clue to what is beneath. In 1913 a well was being drilled for water in this plain on the desert homestead ranch of Dr. John K. Suckow, a physician of Los Angeles. The site of the well was at least a mile from the nearest outcrop of rock. After the drill had gone through the alluvial deposits of sand and gravel that form the surface of the plain and had penetrated the bedrock beneath the alluvium, it struck a hard, crystalline material which proved to be colemanite, one of the hydrous calcium borates.

Since the discovery of the Kramer deposit, wildcat drilling has been conducted in alluvium-covered areas in the surrounding region. However, the absence of any surface indications of buried deposits, the large areas involved, and the great depths at which a similar deposit might occur present serious problems to any wildcat-drilling program.

Logically the first step in the search for a borate deposit of the type being exploited at Boron is to locate the areas in the general region where important amounts of Tertiary sediments occur. The second step is to select the geologic settings from these areas that would favor the accumulation and preservation of a borate deposit. A regional gravity survey of the type described in this report is believed by the author to be the best method yet tested for performing the first step. It is also a valuable tool in performing the second step, but it should be used in conjunction with other techniques.

In the vicinity of Boron and Kramer Junction several test holes in basins inferred from the gravity results have been drilled for the U.S. Geological Survey. The basin 3 miles south of Kramer Junction was tested to a depth of 3,500 feet, but only sandstone conglomerate were found to that depth. The basin 5 miles west of Boron was tested to a depth of 2,328 feet, but the core showed only alluvial sands and silts. In the basin just north of Kramer Junction 3 test holes were put down, the deepest to 3,500 feet; the core of all 3 holes contained lake-bed clays and some colemanite. Further drilling is needed to determine if this basin contains borate deposits of economic value.

In the western Mojave Desert considerable evidence indicates that the low point in a basin of Cenozoic fill may migrate during deposition over a considerable area. Therefore, the fine sediments and salines generally deposited in the low part of a basin are not necessarily confined to the present topographic low area in a basin or the area of thickest fill as indicated by gravity data. Thus, the search for saline deposits should not be confined to areas below the modern playa surfaces or to the thickest Cenozoic section.

Many unsuccessful oil tests have been drilled in the western Mojave Desert. Some of the tests have been drilled at sites selected on the basis of very meager geologic evidence. The western Mojave Desert is not considered by most authorities to be favorable for the origin and accumulation of petroleum deposits. The information inferred from the gravity data relative to the Tertiary deposits, which are most likely source of petroleum, should be helpful in evaluating the possibilities and in locating areas for additional tests.

The relationship between the gravity anomalies and the occurrence and movement of ground water in the western Mojave Desert is not completely understood at present. The relationship is not consistent over all the region, and in large areas little or no data relating to the ground water are available. Most of the ground water being utilized in the region is produced from aquifers within the Cenozoic section. Some of these aquifers receive recharge water from the mountain regions adjoining the desert where precipitation is heavier than on the desert. Other areas are dependent upon local rainfall to sustain the reserves.

In general, ground water moves away from source areas through bedrock channels and structurally low areas. Some of the major bedrock channels and low areas are revealed by the gravity survey even with the spacing of stations used in this survey. However, to define many of the channels adequately, much more detailed coverage would be required. Although no comprehensive study of the hydrology in the western Mojave Desert was made in conjunction with the gravity survey, several of the best water producing areas seem to occur near the margins of the gravity low, probably because coarser materials occur away from the center of the basins. Several faults are known to act as ground-water barriers. If these faults have sufficient vertical displacement, they could be located by gravity measurements.

CONCLUSIONS

In the western Mojave Desert gravity exploration is an effective and economical method of obtaining subsurface information in areas where the cover of Quaternary sediments obscures most of the underlying geology. When considered on a regional scale, the gravity data reveal significant regional trends.

Because the location and extent of the major accumulations of Cenozoic fill can be inferred from the gravity data, these data can make an important contribution to the exploration for, and the development of, the mineral resources occurring within the Cenozoic fill. By indicating the approximate depth of burial of the pre-Cenozoic rock, the gravity data indicate covered areas where it might be feasible to explore for mineral deposits within the pre-Cenozoic rocks.

The geologic information inferred from the gravity data is an important step toward a better understanding of the geology of the western Mojave Desert. This information can serve as a guide to direct more intensive geophysical and geologic studies of the many problems that exist in the region.

SELECTED REFERENCES

Bailey, T. L., and Jahns, R. H., 1954, Geology of the Transverse Range province, southern California: California Div. Mines Bull. 170, chap. 2, p. 83–106.

Benda, W. K., Erd, R. C., Smith, W. C., 1960, Core logs from five holes near Kramer, in the Mojave Desert, Calif.: U.S. Geol. Survey Bull. 1045–F [in press].

Bowen, O. E., Jr., 1954, Geology and mineral resources of the Barstow quadrangle, California: California Div. Mines Bull. 165.

Buwalda, J. P., 1954, Geology of the Tehachapi Mountains, California: California Div. Mines Bull. 170, chap. 2, p. 131–142.

Crowell, J. C., 1952, Geology of the Lebec quadrangle, California: California Div. Mines Spec. Rept. 24.

Dibblee, T. W., Jr., 1952, Geology of the Saltdale quadrangle, California: California Div. Mines Bull. 160.

——— 1957, Simplified geologic map of the western Mojave Desert, California: U.S. Geol. Survey open-file report.

Dobrin, M. B., 1952, Introduction to geophysical prospecting: New York, McGraw Hill, p. 435.

Gale, H. S., 1946, Geology of the Kramer borate district, Kern County, California: California Jour. Mines and Geology, v. 42, p. 325–378.

Hess, F. L., 1910, Gold mining in the Randsburg quadrangle, California: U.S. Geol. Survey Bull. 430, p. 23–47.

Hewett, D. F., 1954a, General geology of the Mojave Desert region, California: California Div. Mines Bull. 170, chap. 2, p. 5–20.

——— 1954b, A fault map of the Mojave Desert region: California Div. Mines Bull. 170, chap. 4, p. 15–18.

Hill, M. L., 1954, Tectonics of faulting in southern California: California Div. Mines Bull. 170, chap. 4, p. 5–13.

Hill, M. L., and Dibblee, T. W., Jr., 1953, San Andreas, Garlock, and Big Pine faults: Geol. Soc. America Bull., v. 64, p. 443–458.

Hulin, C. D., 1925, Geology and ore deposits of the Randsburg quadrangle of California: California Bur. Mines Bull. 95, p. 11–148.

Jahns, R. H., 1954, Investigations and problems of southern California geology: California Div. Mines Bull. 170, chap. 1, p. 5–29.

Mabey, D. R., 1956, Geophysical investigations in the intermontane basins in southern California: Geophysics, v. 21, p. 839–853.

McCulloh, T. H., 1954, Problems of the metamorphic and igneous rocks of the Mojave Desert: California Div. Mines Bull. 170, chap. 7, p. 13–24.

Mumford, R. W., 1954, Deposits of saline minerals in southern California: California Div. Mines Bull. 170, chap. 8, p. 15–22.

Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw Hill, p. 444.

Noble, L. F., 1926a, Borate deposits in the Kramer district, Kern County, California: U.S. Geol. Survey Bull. 785–C, p. 46–61.

——— 1926b, The San Andreas rift and some other active faults in the desert region of southeastern California: Carnegie Inst. Washington Yearbook 25, p. 415–428.

——— 1953, Geology of the Pearland quadrangle, California: U.S. Geol. Survey Geol. Quad. Map GQ–24.

——— 1954a, Geology of the Valyermo quadrangle and vicinity, California; U.S. Geol. Survey Geol. Quad. Map GQ–50.

——— 1954b, The San Andreas fault zone from Soledad Pass to Cajon Pass, California: California Div. Mines Bull. 170, chap. 4, p. 37–38, pl. 5.

Oakeshott, G. B., Braun, L. T., Jennings, C. W., and Wells, Ruth, 1950, Exploratory wells drilled outside of oil and gas fields in California to December 31, 1950: California Div. Mines Spec. Rept. 23, 75 p.

Oliver, H. W., 1956, Isostatic compensation for the Sierra Nevada, California [abs.]: Geol. Soc. America Bull. v. 67, no. 12, p. 1724.

Simpson, E. C., 1934, Geology and mineral deposits of the Elizabeth Lake quadrangle, California: California Jour. Mines and Geology, v. 30, p. 371–415.

Swick, C. H., 1942, Pendulum gravity measurements and isostatic reductions: U.S. Coast and Geod. Survey Spec. Pub. 232, 82 p.

Thompson, D. G., 1929, The Mojave Desert region, California: U.S. Geol. Survey Water-Supply Paper 578.

Troxell, H. C., and Hofmann, W., 1954, Hydrology of the Mojave Desert: California Div. Mines Bull. 170 chap. 7, p. 13–17.

Wiese, J. H., 1950, Geology and mineral resources of the Neenach quadrangle, California: California Div. Mines Bull. 153.

Wright, L. A., and Troxel, B. W., 1954, Western Mojave Desert and Death Valley region: California Div. Mines Bull. 170, Geol. Guidebook 1, 50 p.

INDEX