GEOPHYSICAL FRAMEWORK OF NORTHERN END OF GULF OF CALIFORNIA STRUCTURAL PROVINCE[1]

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ABSTRACT

More than 3,000 gravity observations in the Northern Gulf province, including an underwater gravity survey of the Salton Sea, show the over-all trend of isogal contours to be northwest, parallel to the tectonic pattern dominated by the San Andreas fault system. Contours northeast of the trough trend east, probably reflecting Transverse Range structures in this area. A prominent and linear gradient of 5 mgal/km marks the Banning-Mission Creek fault in the Coachella Valley but dies out southeastward at about the same point the surface trace disappears. The San Jacinto fault zone is characterized by a series of maxima and minima that tend to confirm continuity of this fault zone to the Gulf of California. A 15–20 mgal maximum over the Obsidian Buttes suggests a large anomalous mass at depth, or may be related to contemporaneous metamorphism of the Tertiary sedimentary section that has recently been observed in nearby steam wells. The regional gravity gradient indicates a crustal thickening northwest from the Gulf of California; inferred crustal thicknesses are 32 km at the International Border and 40 km at San Gorgonio Pass. Ten seismic refraction profiles in the Imperial and Coachella Valleys indicate several throughgoing velocity zones, but we are unable to correlate these with known stratigraphic units. The maximum thickness of sediments in the trough appears to be about 6.4 km (21,000 ft) just south of the International Border, with basement becoming shallower both to the north and south. The Salton trough has many geophysical and structural similarities to the Dead Sea rift, but the markedly *en echelon* pattern of major faults in the Salton trough and Gulf of California appears unique. A particular problem is presented by their orientation, which would suggest left-lateral displacement across the zone rather than the right-lateral displacement that is known to characterize at least the northern end of the province.

INTRODUCTION

Although the head of the Gulf of California terminates 100 km south of the International Border, the structural trough characterized by the Gulf continues another 300 km northwest to San Gorgonio Pass (Fig. 1). In this northern segment the trough is filled by Cenozoic deposits derived from the surrounding mountain ranges and from the Colorado River, but the general structural framework appears similar to that of the Gulf of California proper. It is this primarily dry-land segment of the Gulf of California structural province that is the subject of the present study and is herein called the Salton trough. Although considerable geologic work has been done in the various mountain ranges bordering the Salton trough, geophysical studies are necessary within the basin itself because of widespread alluvial cover.

One of the principal objectives of the geophysical study of this region was to gain a better understanding of the nature of the structural control of the Gulf of California. The great linear depression of the Gulf itself is certainly the distinguishing feature of the province, but it is clear from the known geology of mountain ranges bordering the depression that it is not a simple graben, at least at its northern end. The Gulf of California is characterized throughout its length by northwest-trending faults of the San Andreas fault system, but major breaks of this system such as the Banning-Mission Creek, San Jacinto, and Elsinore faults (Fig. 1) which trend at a definite angle to the length of the Gulf, are not simple parallel breaks outlining the borders of a dropped block. It

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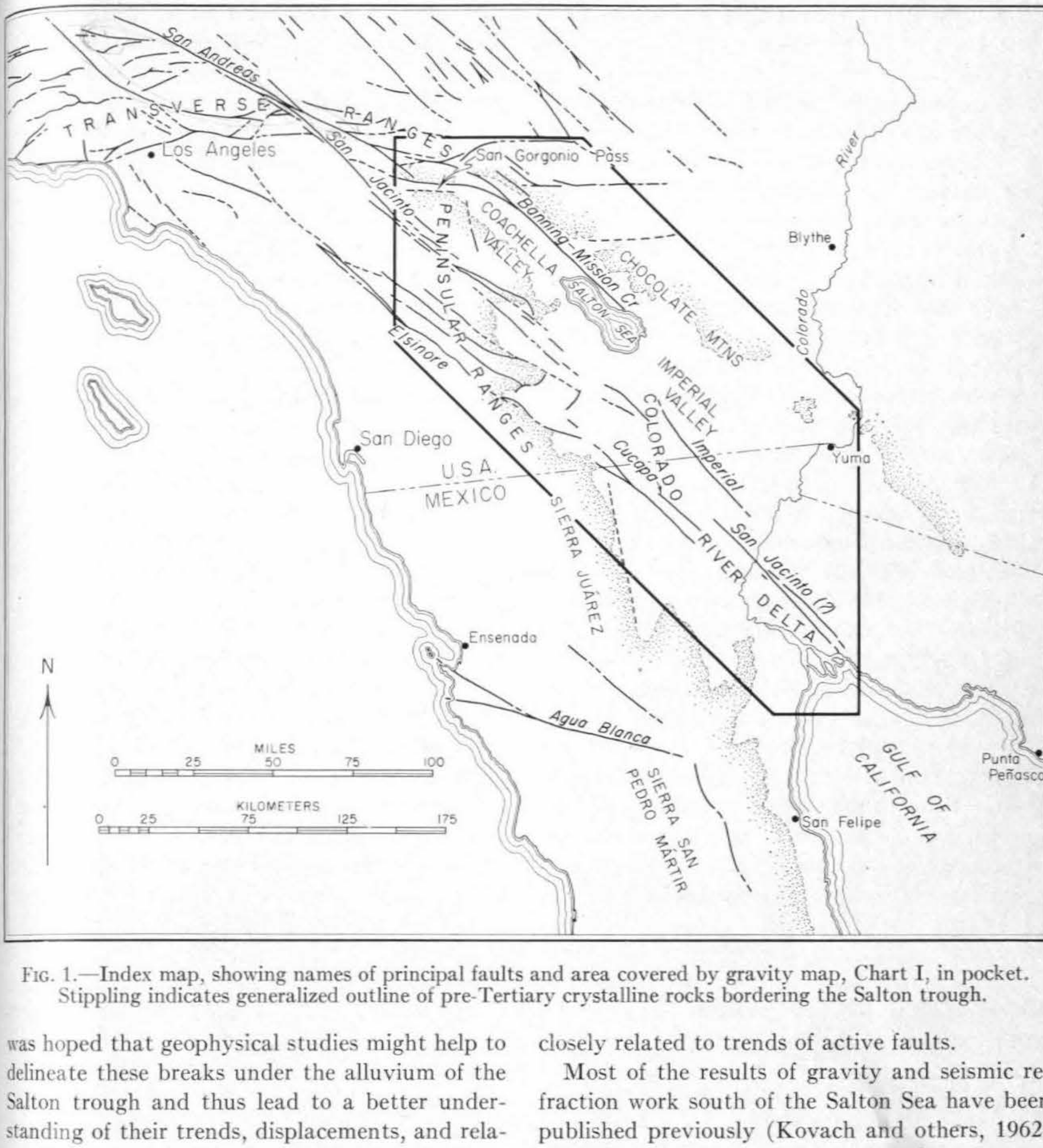

FIG. 1.—Index map, showing names of principal faults and area covered by gravity map, Chart I, in pocket. Stippling indicates generalized outline of pre-Tertiary crystalline rocks bordering the Salton trough.

was hoped that geophysical studies might help to delineate these breaks under the alluvium of the Salton trough and thus lead to a better understanding of their trends, displacements, and relative importance in creating major features of the Gulf province. In addition, the Cenozoic sediments that fill the Salton trough at the northern end have been of considerable interest in themselves, because they include thick marine deposits of potential petroleum importance. Recently, there has been renewed interest in the commercial production of steam from deep wells in the Salton trough both north and south of the International Border. The location of these wells is apparently closely related to trends of active faults.

Most of the results of gravity and seismic refraction work south of the Salton Sea have been published previously (Kovach and others, 1962; Kovach and Monges, 1961) and are merely summarized here. Gravity studies north of this region (by Biehler), including the survey of the Salton Sea, are presented herein for the first time.

TECTONIC FRAMEWORK

Faults.—Even though individual faults of the San Andreas system cannot be delineated everywhere within the Gulf province, the continuity of earthquake epicenters along the axis of the Gulf leaves little doubt that it indeed represents the southeastward prolongation of the San Andreas fault zone. The narrowing and termination of the Gulf province at its northern end, on the other hand, are caused by truncation and conflict between northwest-trending faults of the San Andreas system and east-trending faults of the Transverse Range province. At San Gorgonio Pass these two systems come into conflict with one another, amid great structural complications (Allen, 1957), but southeast of this point, faults of the San Andreas system have remarkable linearity, parallelism, and apparent mechanical coherence. Considerable geologic data, as well as evidence from historic earthquakes and geodetic observations, indicate that the predominant displacements on northwest-trending faults of this region have been right-lateral strike slip. Individual faults of the San Andreas system will be discussed later in this report, where geophysical as well as geological evidence can be considered.

Rocks.—The northern end of the Gulf province is ringed by mountain ranges including the highest peaks of Southern California. West of the Salton trough, these mountains are largely underlain by massive plutonic rocks of the mid-Cretaceous batholith of Southern and Baja California; whereas those to the east comprise more diverse igneous, metamorphic, and volcanic types. As was emphasized by Hamilton (1961), there is no geologic or geochronologic evidence that the Gulf of California necessarily represents the eastern border of the batholith, which may simply be transected and possibly pulled apart by the San Andreas fault system in this region. Nevertheless, all the pre-Tertiary rocks that bound the Salton depression are crystalline types whose geophysical characteristics are in contrast to the Cenozoic sedimentary rocks that constitute the bulk of the material filling the trough. Cenozoic volcanic rocks occur sparsely around the edges of the trough as well as within the sedimentary section of the basin itself. Continued volcanic activity into Quaternary time is indicated by the well-preserved crater of Cerro Prieto, 30 km southeast of Mexicali, and by the very young Pinacate volcanic field north of Punta Peñasco, Sonora (Ives, 1956; Jahns, 1959). In addition, cores from steam wells drilled recently near the south end of the Salton Sea suggest that contemporaneous metamorphism of the Tertiary sedimentary rocks is taking place here, presumably related to magmatic activity at depth (White and others, 1963). Abnormally high heat flow also characterizes the floor of the Gulf of California farther south (von Herzen, 1963).

Detailed stratigraphy of the sedimentary section within the Salton trough is incompletely known, inasmuch as these rocks are only sparsely exposed, and records of the few deep wells within the valley are not easily interpreted. Dibblee (1954) has summarized the known stratigraphy. A major marine incursion of lower Pliocene age from the Gulf is represented by deposits of the Imperial Formation exceeding 3,000 ft in thickness. The subsequent history of deposition has been characterized by intermittent and interfingering deposits derived from local alluvial fans, lakes ancestral to the present Salton Sea, the delta of the Colorado River, and occasional marine incursions from the Gulf of California. Intermittent strike-slip faulting within the basin may have strongly affected original depositional environments, and has subsequently displaced many formerly continuous units, perhaps by several tens of miles.

Seismicity.—In terms of minor and moderate-sized earthquakes, the Salton trough has been the most seismically active part of California and adjacent Mexico within historic time, although no truly great earthquakes have been reported from here (Fig. 2). Several of these shocks have caused considerable damage and loss of life, and the 1940 earthquake on the Imperial fault was associated with well-documented ground displacement for more than 60 km; the International Border was displaced a few meters by right-lateral strike slip at this time (Fig. 3). The 1934 earthquake in the delta region of Mexico was also probably associated with ground displacement (Fig. 4; *see* also Kovach and others, 1962, p. 2848).

The seismicity map of the region portrays a broad band of activity trending southeast into the Gulf of California, but if attention is restricted to earthquakes of magnitude 6 and greater, one finds a remarkable alignment and spacing of earthquakes along the general zone of the San Jacinto fault (Fig. 2). From northwest to southeast, these shocks include the 1918 San Jacinto earthquake

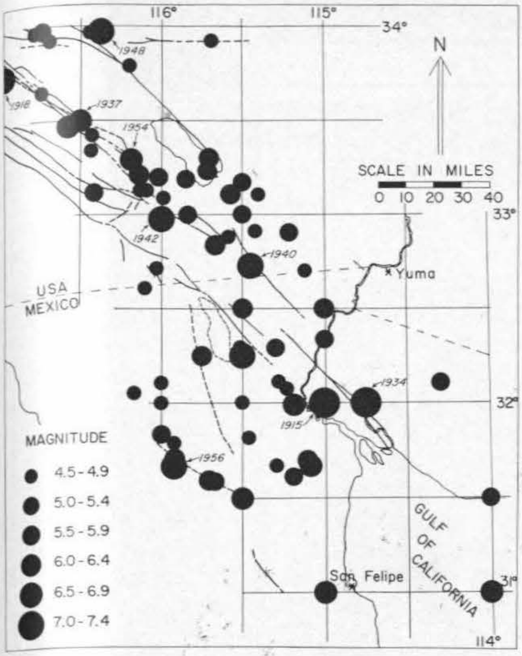

FIG. 2.—Seismicity map of Salton trough and adjacent areas, showing shocks of magnitude 4.5 and greater that occurred between 1904 and 1960. Listing prior to 1934 is very incomplete. Largest shocks, with dates shown, are mentioned in the text. Data from Gutenberg and Richter (1954) and local bulletins of the Pasadena Seismological Laboratory.

(M = 6.8), the 1937 Terwilliger Valley earthquake (M = 6.0), the 1954 Santa Rosa Mountains earthquake (M = 6.2), the 1942 Lower Borrego Valley earthquake (M = 6½), the 1940 Imperial Valley earthquake (M = 7.1), and the 1915 and 1934 earthquakes in the delta region south of the border (M = 7.1; 7.1). Indeed the only large earthquakes of the region that did not occur along the San Jacinto fault zone are the 1948 Desert Hot Springs earthquake (M = 6.5) on the Mission Creek fault and a few very poorly located shocks in Baja California. Some of the earthquakes of the Laguna Salada area just south of the International Border may have occurred on the Elsinore fault. Farther south in Baja California, the 1956 San Miguel earthquake (M = 6.8) was clearly associated with faulting at some distance from the main San Andreas zone, and at a distinct angle to it. References to detailed studies of these various earthquakes are given by Richter (1958).

Geodetic surveys across the Imperial Valley segment of the Salton trough (Whitten, 1956, 1960) indicate that shear strain is continuing to build up in this region. If one compares the rate of strain accumulation with the known strain release through earthquakes, using assumptions similar to those of Benioff (1955), it appears that over a 30-year period roughly as much strain is released

FIG. 3.—Aerial view of orange grove displaced horizontally along Imperial fault during earthquake of May 1940. Photograph taken looking north from about over International Border between United States and Mexico.

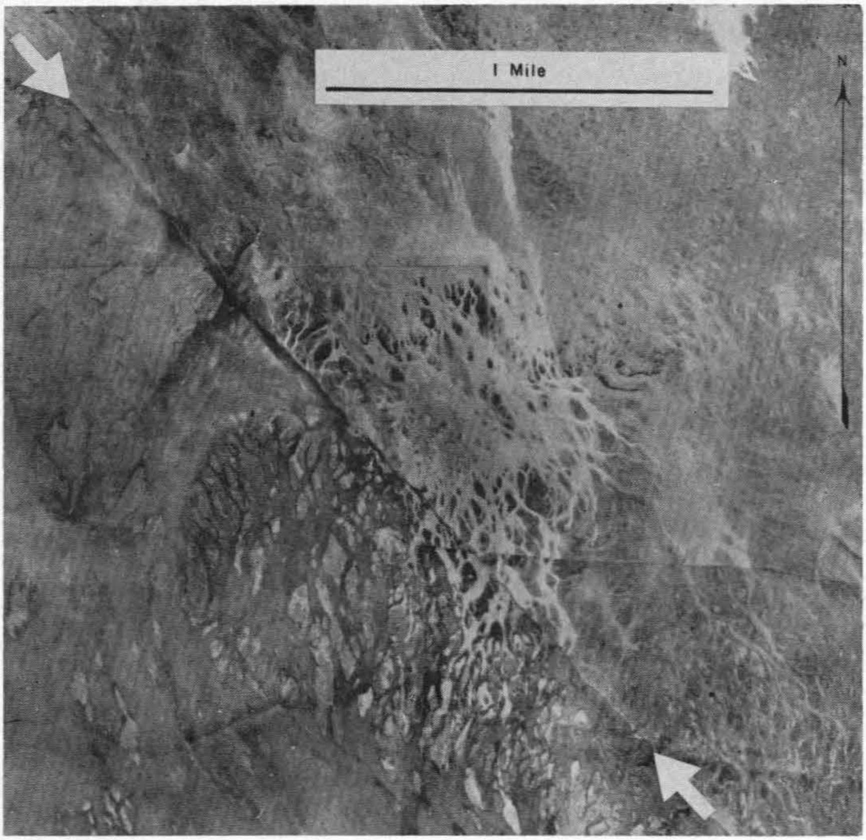

FIG. 4.—Vertical aerial view of San Jacinto? fault where it cuts across tidal flats near the head of the Gulf of California, near lat 31° 50′ N., long 114° 40′ W. This segment of the fault probably broke in the earthquake of Dec. 31, 1934; photograph taken in 1935.

as is accumulated. This is in sharp contrast to the segment of the San Andreas fault zone northwest of this region, where there has been remarkably little seismic activity in the same 30-year period despite the probable accumulation of shear strain across the fault at about the same rate. It appears, therefore, that the typical seismic "habit" of the Northern Gulf province at present is that of relatively frequent moderate-sized earthquakes, as opposed to infrequent great earthquakes along other segments of the San Andreas fault zone.

SEISMIC REFRACTION PROFILES

Ten refraction profiles have been shot within the Salton trough for the purpose of determining the nature of the Tertiary sedimentary section and the depth to the underlying crystalline basement rocks. Six of these profiles, between the International Border and the Salton Sea, were described by Kovach and others (1962); Biehler has subsequently added four more, three of which are around the borders of the Salton Sea, and one of which is north of Indio in the Coachella Valley (Fig. 5). Detailed results of these surveys will be published elsewhere, but the most significant of the new profiles is along an east-west line 2 km north of Westmorland, which was shot to a distance of almost 32 km and for the first time clearly establishes the depth to basement in the very axis of the Salton trough. All other profiles have been shot in desert areas outside the agricultural lands that occupy the floor of the Imperial Valley. Basement arrivals were not reversed along the Westmorland profile, but if basement depth is

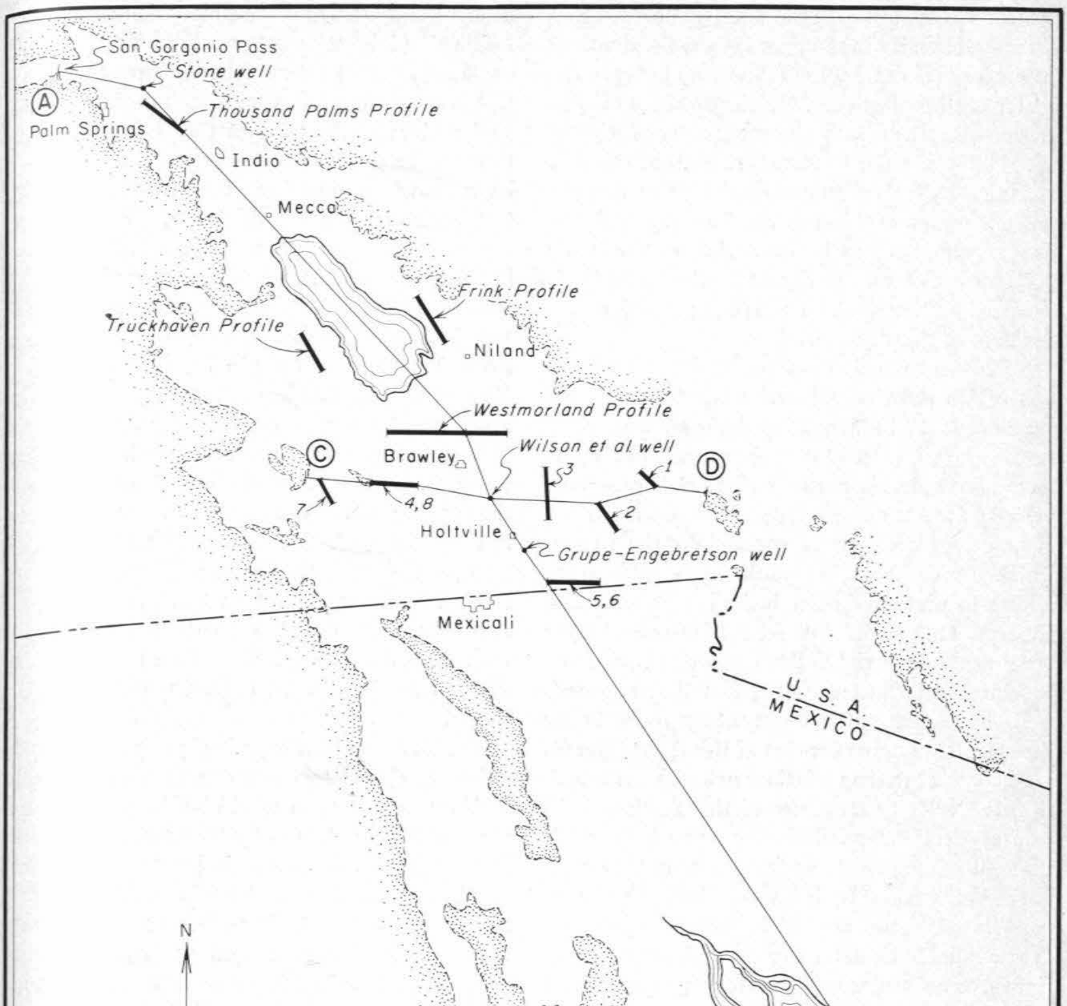

FIG. 5.—Index map of Salton trough showing locations of seismic refraction profiles and cross section lines A–B (Fig. 6) and C–D (Fig. 7). Numbers refer to seismic profiles described by Kovach and others (1962). Reference to Phillips, 1964, is to this volume. Stippling indicates generalized outline of pre-Tertiary crystalline rocks bordering the Salton trough.

projected eastward with the same shallow dip that characterizes all of the upper layers, the depth to basement is about 5.9 km (19,400 ft) beneath the center of the valley (Fig. 6). The presence of clear basement arrivals and the striking similarity of the shallower velocity structure to that of other Imperial Valley profiles suggest that contemporaneous metamorphism of the Tertiary sedimentary section, such as is reported from the steam wells near Niland (White and others, 1963), is localized in "hot spots" and is not pervasive over the floor of the entire valley.

Basement arrivals from the various profiles in this region show seismic velocities varying from 5.2 km/sec (17,100 ft/sec) at the head of the Gulf to 6.4 km/sec (21,000 ft/sec) beneath the Westmorland profile. Such wide variations in basement velocity are not unexpected in view of the variety of basement rock types exposed in the region, which range from low-rank metasedimentary schists to plutonic bodies including granites and gabbros. That the 4.7 km/sec (15,500 ft/sec) layer beneath the Imperial Valley cannot be considered basement is indicated by the fact that two deep wells have penetrated sedimentary rocks below the calculated upper contact of this layer (Fig. 6).

In contrast to the variations in basement velocities, the velocity structure of the Tertiary sedimentary section is so similar from profile to profile that one is tempted to assign stratigraphic names to the individual seismic layers. This has not been possible with the limited subsurface geological data available to date. For example, the Grupe-Engebretson well south of Holtville penetrated four seismic zones (Fig. 6) to a total depth of 3.76 km (12,300 ft) yet all of the rocks from this well were assigned by geologists to a single stratigraphic unit—the Plio-Pleistocene Borrego Formation. If the other formations that are known to underlie the Borrego Formation along the west side of the Imperial Valley are present at depth in the center of the valley, they have not to our knowledge been identified either in wells or in geophysical profiles.

The Westmorland seismic profile has been combined in Figure 6 with others located near the axis of the Salton trough to give a longitudinal cross section from the northern end of the trough at San Gorgonio Pass southeast 400 km to the head of the Gulf of California, where we tie to Phillips' (this volume) northernmost seismic profile. The most noteworthy feature of this section is the greater basement depth in the Imperial Valley than at the head of the Gulf, suggesting that the Salton trough represents a sedimentary basin that is distinct from the rest of the Gulf of California. From our limited data it is difficult to say where the deepest part of the basin may lie, but if basement is projected southward from the Westmorland profile with the same dip that characterizes the shallower layers (Fig. 6), basement would lie at 6.23 km depth beneath profiles 5–6 (Fig. 5) and at 6.37 km (20,900 ft) beneath the broad gravity minimum 20 km farther southeast (Chart I, in pocket). For reasons discussed elsewhere in this report, it is hazardous to assume that gravity directly reflects basement depth, but in the absence of other information in this region we tentatively suggest that this gravity minimum located 35 km east-southeast of Mexicali represents the deepest part of the Salton trough and that the sedimentary section then becomes thinner as traced southeast toward the Gulf of California.

The Thousand Palms seismic refraction profile (Figs. 5, 6) shows basement at a considerably shallower depth than would be suggested by the regional gravity data or by the nearby Stone well. Inasmuch as this profile is located only 4 km southwest of and parallel to the Banning fault—a major branch of the San Andreas—we can only conclude that basement under this profile represents a local faulted block in a zone of complex structure; numerous anomalies on the seismic records from this profile substantiate the idea of structural complications in the basement. Further supporting evidence is given by the magnetic measurements of Soske (1935), which show a distinct magnetic maximum along the axis of the seismic profile.

Figure 7 is a seismic cross section transverse to the axis of the Salton trough near Brawley, based mainly on the refraction profiles of Kovach and others (1962). The basement configuration is undoubtedly more complicated than indicated, inasmuch as the section crosses a number of important active faults; but the section illustrates well the effect observed in many parts of the val-

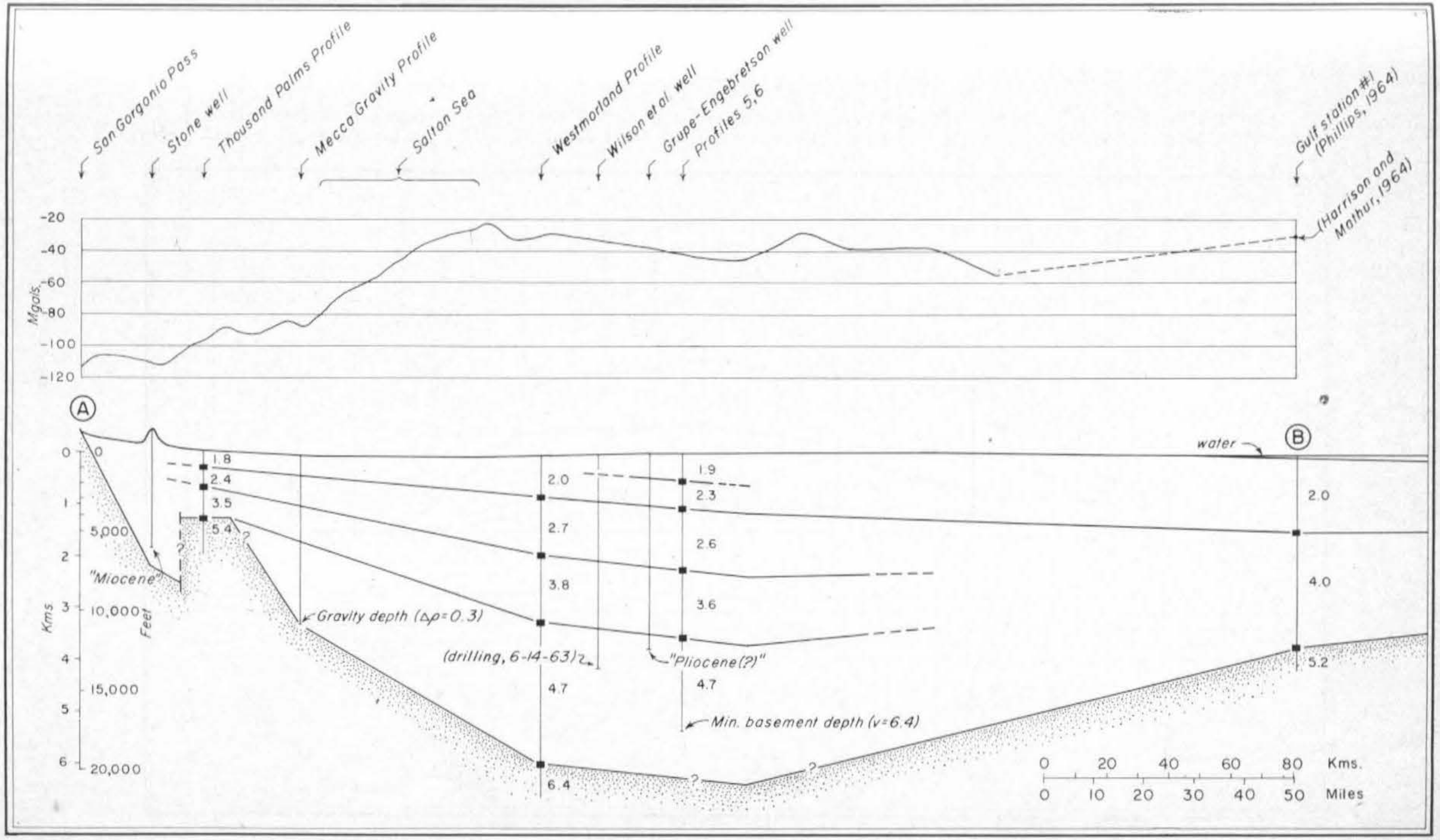

FIG. 6.—Seismic cross section and simple Bouguer gravity profile along line A–B of Figure 5. Numbers indicate velocities in km/sec. References to Phillips, 1964, and Harrison and Mathur, 1964, are to this volume.

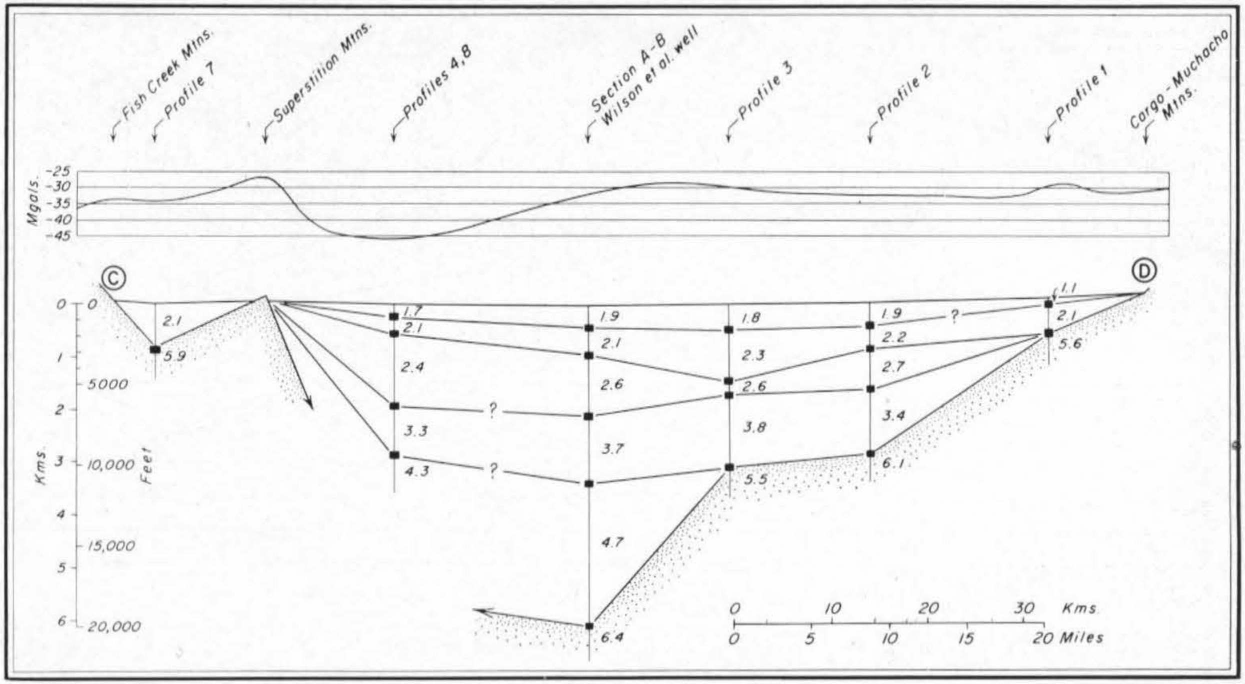

FIG. 7.—Seismic cross section and simple Bouguer gravity profile along line *C–D* of Figure 5.Velocity zones in the middle of the valley are extrapolated from section *A–B*, Figure 6. Note that ratio of horizontal to vertical scales is different on Figures 6 and 7.

ley that some of the seismic layers in the deepest part of the trough are not represented in the shallower areas toward the flanks. If these layers truly indicate stratigraphic units, this pinch-out effect has an important bearing on the sedimentary history of the basin.

GRAVITY OBSERVATIONS

About 3,000 gravity observations were made in the United States and Mexico using a Worden gravimeter (Chart I, in pocket). The observations are tied to a network of base stations in the Salton trough which has been ultimately tied to the University of Wisconsin geodetic base station No. WU4 in Pasadena, California (Behrendt and Woollard, 1961). Adjustment of the 1,250 gravity stations reported in an earlier paper (Kovach and others, 1962) to the University of Wisconsin base station in Pasadena required that about 1.5 mgal be added to the observed gravity values based on this network of gravimeter base stations. However, it should be emphasized that this base station adjustment does not change any of the conclusions reached in the earlier paper, which are all based on a discussion of *relative* Bouguer anomalies. The present map differs from the earlier maps of Kovach and others (1962) in that an elevation factor of 0.060 mgal/ft corresponding to a rock density of 2.67 g/cm^3, has been used in order to facilitate comparison with maps of other workers. The earlier map was reduced using a factor of $0.069 \times 1,000 + 0.060(h - 1,000)$, where h is the station elevation in feet. 0.069 mgal/ft corresponds to a rock density of 2.00 g/cm^3. This change has little effect except for the few stations on the flanks of the Peninsular Ranges west of the Imperial Valley.

The gravity observations in the Salton Sea were made with a LaCoste-Romberg underwater gravimeter, and the gravity stations were located using Tellurometers and transits. The underwater observations are considered accurate to 0.3 mgal.

Station elevations for the land stations in the United States were obtained from survey bench marks, level survey lines, and altimeter readings. In Mexico most of the station elevations were determined by altimeter differences from a network of bench marks of the International Boundary and Water Commission. Considering all the elevation and location factors, the precision of the Bouguer gravity anomalies in the United States is estimated to be 0.3 mgal; in Mexico the precision is estimated to be 1 mgal, although some stations could be in error by more than 1 mgal. The precision of the Mexican stations is hindered by the inadequate maps available.

Terrain corrections have not been made for the gravity stations. Failure to make terrain corrections does not have a significant effect on the majority of the stations, except in the San Gorgonio Pass area and along the extreme edges of the Salton trough. The Bouguer gravity values for these stations would be raised relative to stations in the broad alluviated areas. The average terrain effect in the San Gorgonio Pass area is about 4–6 mgal. Gravity values were reduced to the complete Bouguer anomaly with respect to the International ellipsoid.

GRAVITY INTERPRETATION

Regional anomaly and crustal thickness.—The northwest trend of structural elements of the Salton trough is reflected by the over-all northwest trend of the isogal contours (Chart I, in pocket). Contours in the mountainous area northeast of the Coachella Valley have a general east trend that is in agreement with the major structural features of this area. Thus, in a gross way, the gravity anomalies outline the general tectonic framework that is apparent from the major surface features of the region.

The Bouguer anomalies range from a low of −121 mgal just west of Desert Hot Springs, California, to a high of −10 mgal southeast of Yuma, Arizona. This gravity difference of 110 mgal over a distance of 240 km is an indication of the regional gradient of the area which is approximately parallel to the axis of the Salton trough. The northwest regional gradient is, however, not uniform throughout the length of the trough. From San Gorgonio Pass southeast to about the middle of the Salton Sea, the regional gradient is approximately 0.6 mgal/km; from this area southeast to the International Border the regional gradient is relatively flat—about 0.2 mgal/km. This gradient suggests a very gradual thickening of the crust from the International Border to the Salton Sea and then a more rapid thickening northwest toward San Gorgonio Pass and the northern end of the Salton trough. However, this is based on regional gravity values on pre-Tertiary crystalline rocks and may reflect the crustal thickness under the mountains along the flanks of the trough and not under the Salton trough itself.

Assuming a crust-mantle density contrast of 0.3 g/cm^3, a crustal thickening of about 8 km is needed to explain a regional anomaly of 100 mgal. If a density contrast of 0.4 g/cm^3 is assumed, then a thickening of only 6 km is necessary. From Woollard's (1959) empirical curve relating Bouguer anomaly to crustal thickness, a -110 mgal anomaly indicates a crustal thickness of about 40 km, and a -10 mgal anomaly a thickness of 32 km; this is consistent with the above simple computation.

Unfortunately, the sparsity of gravity data and the large distances involved do not justify a detailed extrapolation of our data to the area studied by Harrison and Mathur (this volume) at the head of the Gulf of California. However, the average Bouguer gravity at the head of the Gulf is about 10 mgal higher than at the International Border, which is in agreement with the concept of a continental crust thinning toward the southeast. Seismic refraction measurements (Phillips, this volume) verify that a thin crust is present beneath the Gulf south of lat 27° 30′ N., and that the crust becomes progressively thicker and more continental toward the northern end of the Gulf.

Thickness of sediments.—The problem of estimating thickness of sedimentary fill in the Salton trough from gravity data alone is a hazardous one, as has been emphasized by Kovach and others (1962). Peculiar problems of this region include (1) known density complications, such as reversals with depth, in the sedimentary section; (2) abrupt facies changes that occur throughout the basin; (3) a wide variety of crystalline rock types constituting the regional basement, ranging from granite to gabbro to low-rank metasedimentary schists, many of which are in complex fault relationship to one another; (4) volcanic rocks that are known to occur locally within the section; (5) recently documented contemporaneous metamorphism of parts of the Tertiary section, with markedly increased densities relative to unmetamorphosed parts of the section; and (6) the possibility of local isostatic compensation beneath the trough.

In some areas the gravity contours appear directly to reflect the basement configuration, but marked failure to do so in other areas causes hesitancy in drawing general conclusions from the gravity map. For example, gravity values across the eastern half of the Imperial Valley near Holtville (Fig. 7) are nearly constant and have little apparent relation to basement depths that are here well documented from seismic data. Undoubtedly one contributing factor is the presence of deep high-velocity zones in the sedimentary section that are restricted to the central parts of the basin; sedimentary rocks with seismic velocities of 4.7 km/sec (15,400 ft/sec) may well have densities above 2.6 g/cm^3 (Woollard, 1962), which is as high a density as that of some of the basement rocks of the region. Thus in computing a depth to basement on the basis of a single density contrast, we are in some areas undoubtedly "seeing" horizons that are within the sedimentary section rather than the true crystalline basement.

The problem of increased density associated with contemporaneous metamorphism of the Tertiary section near Obsidian Buttes is discussed elsewhere in this report, but it is obvious that the possibility of similar effects elsewhere in the Salton trough adds to both the interest and the hazards in gravity interpretation. In the absence of heat-flow measurements, we cannot say whether or not some of the other gravity maxima might be related to similar magmatic effects, but it is clear that generalized conclusions as to depth to basement cannot be drawn until more is known of this problem.

Banning-Mission Creek fault and Coachella Valley area.—The Banning-Mission Creek fault is the most northeasterly representative of the San Andreas system in the Gulf province and indeed has often been called *the* San Andreas fault in this region. The fault is particularly well exposed near Indio (Fig. 8), but as traced southeast the surficial evidence for faulting dies out abruptly near Pope (Chart I, in pocket). This is disturbing because the fault near Indio possesses many features characteristic of the fault in its "type area" in central

FIG. 8.—Aerial view of Banning-Mission Creek fault 5 km northeast of Indio, in the area of the greatest magnetic and gravity anomalies across the fault. Photograph taken prior to excavation of the Coachella Canal in this area.

California—the trace is exceptionally linear; scarps are continuous and well developed; and right-lateral stream offsets are particularly evident in the Indio Hills (Popenoe, 1959). Furthermore, very large lateral displacement along this fault zone has been suggested by Crowell (1962) on the basis of similar geologic terranes north of the fault in the Salton Sea area and south of the fault in the central Transverse Ranges; this appears to be incompatible with the fault terminating abruptly at the Salton Sea. If the fault is projected southeast in line with its very linear trace where well exposed, it would miss the northern end of the Gulf of California entirely and extend into Sonora. However, there is no presently known geologic or seismic evidence for continuing this fault into Sonora. Much of this region, however, is covered by wind-blown sand, and portions south of the International Border have not been mapped geologically even in reconnaissance. Toward the northwest, the two branches of the Banning-Mission Creek fault diverge and veer westward into the complex region of San Gorgonio Pass, becoming north-dipping thrusts (Allen, 1957).

A steep gravity gradient of about 5 mgal/km characterizes the Banning-Mission Creek fault from the point where the two faults coalesce southeast to the Salton Sea. This steep gradient indicates a near-surface anomalous mass probably caused by higher density basement rocks northeast of the fault being juxtaposed against thick sedimentary rocks of the Coachella Valley across the fault to the southwest. Preliminary calculations based on simple Bouguer anomalies and assuming a density contrast of 0.3 g/cm^3 indicate a depth of fill of 3.2 km (10,500 ft) at Mecca; a density contrast of 0.2 g/cm^3 would nearly double this depth. At the southern end of the exposed trace of the fault near Pope the gravity gradient dies out, and the contours swing sharply southwestward. This may be due in part to the influence of the large gravity maximum over the Obsidian Buttes at the south end of the Salton Sea. Even southeast of the Obsidian Buttes, however, there is no indication of a steep gravity gradient along the projected trace of the fault similar to the gradient farther north.

It is significant that in the 14 magnetic profiles across the fault in this region that were described by Soske (1935), the greatest magnetic anomalies occur across the fault near Mecca—in the same area as the most pronounced gravity anomalies. Furthermore, the magnetic anomalies gradually dissipate southeastward, and Soske's long profile across the Imperial Valley south of the Obsidian Buttes shows no marked magnetic anomaly across the projected trace of the Banning-Mission Creek fault in this area.

A gravity gradient similar to that along the Banning-Mission Creek fault exists on the opposite side of the Coachella Valley but is neither as steep nor as continuous. This probably indicates a fault system along the front of the Santa Rosa Mountains that is buried beneath the alluvium at shallow depth. Discontinuities in the trend of the gradient are possibly caused by cross faults that strike northeast, similar to the fault exposed northwest of Truckhaven.

The large gravity maximum north of Truckhaven is of the same magnitude as the maximum on the opposite side of the Salton Sea, and a similar maximum is present just northeast of Borrego Springs. These closures are all located over localized exposures of metamorphic rock and may reflect a higher density as compared to the surrounding granite intrusive rocks.

Obsidian Buttes area.—A large gravity maximum of 15–20 mgal is present over the Obsidian Buttes (Salton volcanic domes) at the southern end of the Salton Sea. Although the surface expression of volcanic activity appears to be along a line trending northeast, the gravity anomaly indicates an approximately circular mass distribution. The center of the anomaly is located about 2 km east of Red Island, which is near the middle of the linear distribution of the four buttes. Undoubtedly, part of this gravity maximum is due to volcanic rocks which have a higher density than that of the surrounding sediments. However, a larger contributing factor to the mass anomaly may be the increased density of sediments that are undergoing contemporaneous metamorphism in this area (White and others, 1963). The density of these metamorphosed sediments is approximately 0.3 to 0.4 g/cm^3 greater than that of the equivalent unaltered rock. Assuming a density contrast of this magnitude, a considerably larger anomalous mass is necessary to explain the gravity maximum than is indicated by the surface exposure of the domes; such an explanation is in agreement with the magnetic observations of Kelley and Soske (1936). The broadness of the anomaly indicates that the center of the mass may be located at considerable depth, possibly as deep as 5 or 6 km with an equal lateral subsurface extent. Alternatively, this broadness may be the result of a horizontal decrease in the density of the altered sediments outward from the center of metamorphism. More detailed geophysical studies of this area are currently underway and will be published elsewhere.

San Jacinto fault.—The San Jacinto fault zone is probably the straightest and most throughgoing member of the San Andreas system in southern California, although even it cannot be followed continuously into the Gulf of California. Conspicuous features of recent displacement mark the trace of the fault southeast from where it diverges from the main San Andreas, across the high Peninsular Ranges, and into the Borrego-Clark Valley area. Here the fault seems to fray out into several branches, all of which lose surface expression as traced toward the International Border. Southeast from Cerro Prieto, 30 km south of the Border, a distinct surface break can be followed continuously for the remaining 100 km to the Gulf of California (Fig. 4; Kovach and others, 1962). This segment has tentatively been called the San Jacinto fault on the basis of its close alignment to the trend of the fault where well exposed in the Peninsular Ranges to the northwest and because of the continuity of earthquake epicenters along the zone. If continuous, however, the fault must be characterized by a wide zone of fractures, and the faults of the Superstition Mountains and possibly even the Imperial fault must be considered members of the San Jacinto zone. It is interesting to note that if the San Jacinto fault is projected into the Gulf of California along the line of very linear scarps in the delta region, it does not parallel the axis of the Gulf, but instead cuts across the northeast corner of the Gulf and into Sonora.

In the high Peninsular Ranges the San Jacinto fault is characterized by a series of small gravity lows along the length of the zone. There is no pronounced gradient such as is seen across the Banning-Mission Creek fault. In this area the entire fault zone is located in pre-Tertiary crystalline rocks, and as a result the absence of large density contrasts is not surprising. The presence of gravity lows may indicate a slightly lowered density of the crushed rocks within the fault zone.

Southward in the Borrego Valley area a steep gravity gradient is present between the minimum of Borrego Valley and the maximum over the metasedimentary rocks of Coyote Mountain, 10 km northeast of Borrego Springs. From here south to the International Border the fault zone is characterized by numerous gravity maxima and minima, including the minimum in Lower Borrego Valley, the maximum over the Superstition Mountains, the minimum west of El Centro, and the maximum near Mexicali. These highs and lows are evidently indicative of small uplifted and downdropped blocks, such as are typical of the San Andreas fault zone where better exposed elsewhere in California. A relatively steep gravity gradient is seen along the projection of the San Jacinto fault in Mexico between Cerro Prieto and Mexicali, and a buried 2 km scarp along the fault is indicated by gravity data near Victoria (Kovach and others, 1962, Fig. 15).

Elsinore-Laguna Salada fault.—Unlike the Banning-Mission Creek and San Jacinto faults, the Elsinore fault does not coalesce with the San Andreas fault as traced toward the northwest. Its assignment to the San Andreas system is instead based primarily on its being one of the *en echelon* fractures of the system farther south in the Gulf of California province. The Elsinore fault is marked by evidence of recent displacements throughout most of its trace through the batholithic rocks of the Peninsular Ranges (Jahns, 1954; Dibblee, 1954), and it lines up very closely with the Laguna Salada fault of Baja California—a correlation that is supported by the gravity data. The Laguna Salada fault is best exposed in the Sierra de los Cucapas, but this range is typical of other structural features of the Gulf province in being oriented more northerly than the obvious through-going faults of the area—that is, northwest-trending fractures such as the Laguna Salada and Cucapa faults (Fig. 9) appear to cut across the trend of the range rather than completely delineating its borders; other less obvious fractures of different orientation must be present beneath the bordering alluvium.

The steep gravity gradient along the southwest flank of the Sierra de los Cucapas is one of the most noteworthy features of the gravity map. Although the detailed configuration of contours is obviously not well defined by the available stations, it is clear that a very steep gradient must exist and that its average trend is more northerly than that of individual breaks such as the Laguna Salada fault. The gradient suggests a depth to basement of about 5.8 km (19,000 ft) in Laguna Salada (Kovach and others, 1962, p. 2870), although any estimate is difficult without a better knowledge of gravity values west of Laguna Salada toward the Sierra Juárez.

East-trending faults of the Little San Bernardino Mountains.—Three east-trending lineaments dominate the structure of the mountainous country northeast of the Banning-Mission Creek fault. The northern two, through Twentynine Palms and through the Pinto Basin, are distinct fault zones marked by Recent scarps and crushed zones; the southern lineament, between Indio and Desert Center, is inferred to be fault controlled because of the gross physiography. These three zones are particularly interesting because they appear to indicate continuity of east-trending structures of the Transverse Range province into this region, possibly offset somewhat to the south by the San Andreas fault. The Transverse Ranges, in turn, probably represent the continental prolongation of the offshore Murray fracture zone, so that very major and deep-seated tectonic features may be represented by these lineaments. They certainly extend east beyond the area of Chart I, but their total extent is unknown.

The fault zone through the Pinto Basin, called the Eagle Mountain lineament by Hill (1928) and

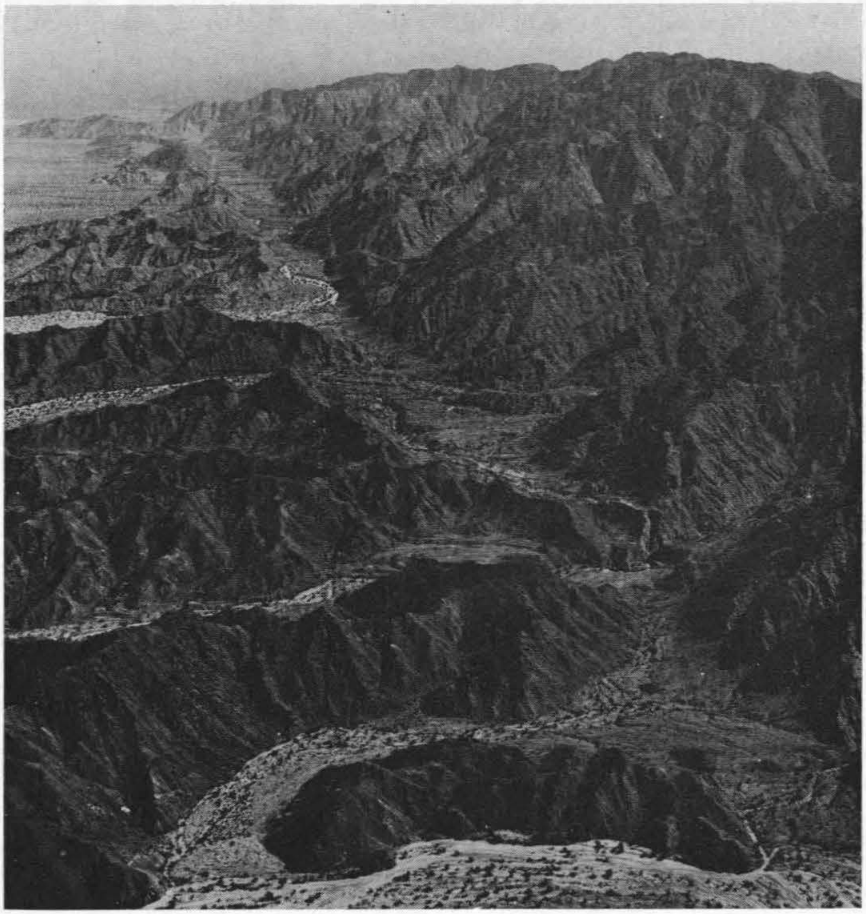

FIG. 9.—Aerial view southeast along Cucapa fault, 25 km south of Mexicali, Baja California. Trench is caused primarily by erosion of crushed rock within the fault zone, rather than by Recent fault displacements.

apparently including the Blue Cut fault of Pruss and others (1959), has a particularly marked gravity effect. The three traverses that cross the fault all show a distinct minimum at the fault, although additional work will be necessary to delineate the anomaly completely, particularly as traced west toward Desert Hot Springs. A less pronounced gravity low occurs along the lineament between Indio and Desert Center, but data are insufficient to make any comment on possible anomalies along the northernmost lineament. Certainly the over-all east trend of contours in the northeast segment of the gravity map is in contrast to the northwest trend that characterizes the Salton trough, and it tends to confirm the geological observation that a grossly different tectonic pattern—perhaps related to the Transverse Ranges—typifies this northeastern region.

REGIONAL COMPARISONS AND PROBLEMS

It is tempting to compare the Salton trough with other regions in the world of possible similar tectonic setting. However, the Gulf of California province, including the Salton trough, appears to be unique in that it combines some of the attributes of rift valleys with those of major strike-slip fault systems, and in this respect is not directly comparable to features such as either the East African rift valleys or the northern part of the San Andreas fault zone. Perhaps the most intriguing comparison is with the Dead Sea rift of the Near East, which has many striking analogies to the Salton trough.

(1) Both are sediment-filled troughs, in part below sea level, characterized by great length and linearity and by steep fault-controlled valley walls.

(2) Although current seismicity is considerably lower in the Dead Sea rift than in the Salton trough, the presence of numerous Recent scarps and closed depressions in both these regions testifies to vigorous continuing tectonic activity.

(3) Both troughs have been ascribed to rifting and extension, but evidence of a significant strike-slip component has been recognized in recent years in both areas, with possible total displacements of at least 260 km (right-lateral) for the Salton trough (Crowell, 1962) and 107 km (left-lateral) for the Dead Sea rift (Quennell, 1959).

(4) As traced southward toward the open ocean, both rift zones become progressively wider, suggesting rotation of adjacent continental blocks (Hamilton, 1961; Quennell, 1959). Furthermore, crustal structure becomes progressively more oceanic in character toward the south (Drake and others, 1959; Nafe and others, 1959; Phillips, this volume).

(5) Relative Bouguer gravity minima characterize both rift zones, with negative anomalies of 50–100 mgal reported from the Gulf of 'Aqaba and Lebanese segments of the Dead Sea rift (de Bruyn, 1955; Girdler, 1958), and similar values from parts of the Salton trough. On the other hand, southward from each of these areas, in the wider and more oceanic parts of the rift structures —the Red Sea and the Gulf of California—the Bouguer anomalies change from negative to positive, with definite relative gravity maxima along the axes of the rifts (Girdler, 1958; Harrison and Mathur, this volume).

(6) Although striking magnetic anomalies are present over the median rift valley of the Red Sea, these anomalies die out northward and do not characterize either the Gulf of Suez or the Gulf of Aqaba (Drake and others, 1959; Girdler, 1962). Likewise, Soske's (1935) 50-mile profile across the Imperial Valley of the Salton trough shows no linear magnetic anomalies that are at all comparable to those of the Red Sea or some of the mid-ocean ridges. Preliminary analysis by Hilde (this volume) of magnetic measurements by R. Warren in the Gulf of California south of Guaymas indicates sharp magnetic anomalies associated with submarine scarps and basins in this area.

Despite the many similarities, there remain some significant contrasts between the Salton trough and the Dead Sea rift that imply fundamental tectonic differences. The Salton trough is collinear with the Gulf of California and appears to share its structural pattern in every way, whereas the Dead Sea rift is at a marked angle to the Red Sea. Left-lateral displacement along the Dead Sea rift is thus mechanically compatible with almost pure extension across the Red Sea, as has been pointed out by a number of workers. Such is not the case in the Gulf of California, where right-lateral displacement across the Salton trough suggests that the same sense of displacement characterizes the entire Gulf province.

One of the most intriguing aspects of the structure of the Gulf of California is the *en echelon* fault pattern, in that major faults of the trough trend more westerly than the axis and borders of the trough itself. In the Salton trough, these breaks are typified by the Banning-Mission Creek, San Jacinto, and Elsinore faults, and the submarine topography of the floor of the Gulf (Rusnak and others, this volume) leaves little doubt that the same pattern characterizes most of the rest of the Gulf province as well. At least at the northern end of the province, these *en echelon* faults clearly cut across the adjacent mountain ranges and are by no means limited to the floor of the trough itself.

Subsidiary *en echelon* breaks associated with great strike-slip faults are not in themselves unusual, and indeed are reported from the region of the Dead Sea rift (Vroman, 1961, p. 329). Those of the Gulf of California, however, can hardly be considered "subsidiary," inasmuch as there is no one throughgoing master fracture, at least at the surface. Nor has such a pronounced *en echelon* pattern been recognized in any of the other major circum-Pacific strike-slip fault zones that are otherwise very similar to the San Andreas (Allen, 1962). But the most puzzling aspect of the faults of the Gulf of California is that the *en echelon* pattern is in the wrong orientation for right-lateral displacements across the zone and would instead suggest left-lateral movements. That is, a regional stress pattern oriented so as to produce right-lateral displacement across the Gulf of California would seemingly lead to *en echelon* fractures trending more northerly than the Gulf axis (*see* Hills, 1953, p. 132–133) if these *en echelon* fractures are at all similar in origin to those that have consistently been observed in glaciers, ore deposits, dike swarms, earthquake fractures, and numerous model studies. Even though one might argue that the sense of displacement across most of the Gulf of California has not been documented and could indeed be left-lateral, this cannot be claimed for the *en echelon* faults of the Salton trough, which are not only clearly right-lateral, but have apparently had a long history of such displacement. Furthermore, the relative motion between opposite walls of the Salton trough is likewise right-lateral, as demonstrated by geodetic observations (Whitten, 1956, 1960), which is important because one might otherwise argue that right-lateral displacement on *en echelon* faults within the trough is the result of rotation of these faults in response to left-lateral displacement across the zone as a whole.

Perhaps the answer to the anomalous *en echelon* pattern is that present displacements are associated with faults that were initially formed under a very different stress system, or that possibly different members of the system have originated sequentially at different times. On the other hand, there is no known geologic evidence for either of these hypotheses, and it is significant that all of the faults are apparently active at the present time.

An important difference between the San Andreas fault zone in the Gulf of California and in its "type area" in central California is the abundant evidence for extension perpendicular to the fault zone in the Gulf, possibly associated with the prolongation of the East Pacific Rise into this region (Menard, 1960). Supporting evidence of extension is given by Quaternary volcanism, which is absent along the San Andreas zone north of the Salton trough but is relatively abundant within the trough and farther south. Other geologic contrasts have been cited by Hamilton (1961), who pointed out that the Transverse Ranges mark the dividing line between these two structural realms of the San Andreas fault. It seems reasonable that the extensional history of the Gulf has had a direct bearing on the development of the unique *en echelon* pattern, but no known mechanical model combining extension with right-lateral displacement satisfactorily explains the existing pattern. Shepard (1950, p. 17–19) pointed out that the deep rhomb-shaped basins of the Gulf may have resulted from tensional forces set up between adjacent parallel strike-slip faults, and this explanation may well apply to the dropped blocks of the Salton trough as well. The origin of the major *en echelon* faults themselves, however, remains an enigma.

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