GEOPHYSICAL INVESTIGATIONS IN THE COLORADO DELTA REGION

Thesis by

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ABSTRACT

The combined approach of gravity and seismic refraction exploration was used to determine depths of the Cenozoic section and to study the fault pattern in the Colorado Delta region. Basement depths measured varied from about 2200 feet to a minimum depth of 15,400 feet along the international border, east of Calexico. A study of the seismicity of the region shows that the greatest seismic activity over the past 60 years has been along the San Jacinto fault system. Continuity of specific major faults is difficult to establish using gravity methods alone because of the lack of indicated vertical throw on the faults. No conclusive evidence is presented for establishing the continuity of the Mission Creek - Banning fault southward into the present area of investigation, although geophysical evidence is presented for a fault present beneath the Sand Hills (Algodones Dunes).

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INTRODUCTION

The Colorado Delta region is part of the complex structural trough which continues northwesterly from the Gulf of California. Sedimentation has occurred in this part of the trough intermittently since Miocene time, yet surprisingly little is known of the thickness or configuration of the Cenozoic rocks. Since the Cenozoic section rests upon pre-Tertiary igneous and metamorphic rocks in some areas and is in fault contact with the pre-Tertiary rocks in other areas, a knowledge of the thickness of the Cenozoic section is necessary for deciphering the structural and stratigraphic history in the delta region. Because of the lack of geologic outcrops one must turn to geophysics as a means of investigation.

As part of a continuing program, the California Institute of Technology has been involved in a study of basin structures in the California-Nevada region by utilizing the combined approach of gravity and seismic exploration.

About 1200 gravity observations were obtained in the delta region and eight seismic refraction profiles were shot. These results coupled with available well data are used to determine depths of the Cenozoic section and to study the fault pattern in the delta region.

GEOLOGY

General Geologic Setting

The area investigated in this study is part of the Gulf of California structural province and extends from about 32° 00' to 33° 10' north latitude (Fig. 1). We refer to this region as the Colorado Delta area because the structural trough that extends northwest from the Gulf of California is here filled by the combined fan and delta of the Colorado River. The apex of this great deltaic cone is at the eastern edge of the trough near Yuma, Arizona, and the delta forms a natural dam that prevents marine waters of the Gulf of California from flooding the depressed Salton Sea area north of the delta. Within recent geologic history, the Colorado River has taken various paths across its deltaic cone, at times emptying into the Gulf of California and at times emptying into the land-locked Salton Sea. The sediments and well-preserved shorelines of the region reveal a complex physiographic-depositional history that has been especially studied by Sykes (1937), Hubbs and Miller (1948), and Longwell (1954). The present Salton Sea dates from accidental diversion of the Colorado River in 1905-1907, although the lake is now sustained by drainage waters from irrigation. The latest marine incursion into the Salton Sea area was in middle Pleistocene time (Downs and Woodard, 1961), and earlier intermittent marine incursions evidently took place at least as long ago as Late Miocene time.

In addition to the mountain ranges which bound the delta region (Fig. 1), several small but rugged ranges are found within the area of investigation. These include the Superstition Mountains, the Cargo Muchacho Mountains, the Sierra de los Cucapas, the Sierra Mayor and the Sierra Pinta. A prominent landmark in the region south of Mexicali is Cerro Prieto, a large volcanic cone located east of the Cucapas rising from the alluvial plain which surrounds it. Laguna Salada, a large lake bed lying below sea level between the Sierra Juárez and the Sierra de los Cucapas, connects to the tidal flats of the Gulf of California and is occasionally flooded by a combination of tidal effects and backwash from the Colorado River. Several volcanic domes of pumice and obsidian are found at the southern end of the Salton Sea and rise to an elevation of 100 feet above the valley floor.

Blake (1857, 1914) made an early systematic study of the region north of the international boundary and this work was followed by Augur (1920), who discussed the oil possibilities and historical geology of the Imperial Valley. Brown (1922) and Noble (1926) discussed the fault features in the region. Henshaw (1942) studied the geology of the

Cargo Muchacho Mountains. Interest in the oil possibilities of the Imperial Valley has been intermittent and has led to detailed mapping of the west side of the valley (Tarbet and Holman, 1944; Tarbet, 1951). Wood (1941, 1942) has studied the seismicity of the Imperial Valley. Dibblee (1954) gives an excellent summary of the stratigraphy and areal geology of southwestern Imperial Valley. Recently Woodard (1961) has suggested revision of the stratigraphic section on the southwest side of the Imperial Valley.

The area south of the international boundary is little known. Cosby (1929) studied the geography of Laguna Salada. Kniffen (1932) and Sykes (1937) discussed the physiography and geomorphology of the delta region south of the international boundary. No adequate geologic mapping has been done in this portion of Baja California and any field work is hindered by the lack of base maps for control. Beal (1948) briefly summarizes some early reconnaissance work in this region.

Rocks of the Area

A more complete description of the stratigraphy of the Imperial Valley region than that given here may be found in Tarbet (1951) and Dibblee (1954) together with the recent work of Woodard (1961), Durham and Allison (1961), and Downs and Woodard (1961).

The Peninsular Ranges and their southern continuation, the Sierra Juárez, are underlain by crystalline rocks of the great mid-Cretaceous batholith of southern California and Baja California, together with pre-batholithic metasedimentary and metavolcanic rocks. The principal rock types present in the batholith are gabbro, tonalite and granodiorite (Larsen, 1948).

The sediments within the Cenozoic section, in the southwestern Imperial Valley region along the edge of the sedimentary basin, can be divided into five formations. The Split Mountain formation (Miocene?), composed of non-marine fanglomerates and diorite breccia, varies in thickness from 0 to 2700 feet and rests directly on the basement complex.

The Alverson Canyon formation (Miocene?), which may be equivalent in age to the Split Mountain formation, consists of non-marine sandstones and conglomerates and andesitic lava.

The Imperial formation (Late Miocene or Early Pliocene) is the most important formation deposited under a marine environment and unconformably overlies all the older rocks. It is composed of sandstones, mudstones, siltstones and fossiliferous reefs and has a maximum exposed thickness of about 3600 feet.

Terrestrial sandstones and red clays of the Palm Spring formation (Pliocene-Pleistocene) overlie the Imperial formation. The maximum exposed thickness is at least 6100 feet. Some marine fossils are found in the Palm Spring formation (Tarbet, 1951; Downs and Woodard, 1961) suggesting that the formation grades laterally into marine sediments.

Unconformably overlying all the older formations is the Borrego formation of Pliocene or Pleistocene age. The Borrego formation is composed of sandstones, mudstones, clays and conglomerates and has a maximum exposed thickness of at least 8600 feet.

It is important to point out that the stratigraphic section described above is that exposed along the southwest edge of Imperial Valley, where the section is upturned at the edge of the depositional basin. In the central part of the valley the section may be complicated by possible interfingering with deltaic sediments of the Colorado River and by the effects of major strike-slip faults. Several deep wells were drilled in the central part of Imperial

Valley and passed through a succession of non-marine sandstones and shales identified as belonging either to the Palm Spring or Borrego formation. It is interesting to note that the presence of the marine Imperial formation has not heretofore been demonstrated in the central part of Imperial Valley. However, A. T. Van Huisen (personal communication) recently reports that marine fauna identified as belonging to the Imperial formation were found in his Sardi well and his Sinclair well (Kent Imperial Oil Co.), west of Calipatria. The Imperial formation was also identified in the Federal 1 well (see Table 1) south of Yuma, Arizona.

Since the region south of the international boundary is imperfectly known, little can be stated concerning the rock types present. The Sierra de los Cucapas is mainly composed of plutonic rocks and pre-batholithic metasedimentary rocks, including abundant marbles and quartzites. Pre-batholithic amphibolitic schists and Cenozoic volcanic rocks underlie the Sierra Pinta southeast of Laguna Salada.

Pumice and obsidian domes (Pleistocene) are found just south of the Salton Sea. Cerro Prieto, the large volcanic cone located south of Mexicali, is probably Quaternary in age as is evidenced by its crater shape and its associated mud volcanoes. Pleistocene and Recent alluvium cover most of the province.

Structure

Many early writers (Brown, 1922; Noble, 1926; Reed, 1933; Willis, 1938; Beal, 1948) have already discussed the obvious dominance of faults of the San Andreas system in the delta region. Shown in Figure 2 are the primary faults of the region evidenced from the surface geology.

One is immediately impressed by the overall northwesterly trend of faults in the region. This fact has led many geologists tacitly to assume that the region is merely a sequence of downdropped fault blocks. The type and amount of movement on faults of the San Andreas system in the province are often difficult to establish; most evidence points to right-lateral movement (Dibblee, 1954).

As pointed out by Allen (1957), southeast of San Gorgonio Pass it is not clear which fault trace should be termed the San Andreas fault. For this reason the author also prefers to call the fault along the east side of the Salton Sea the Mission Creek-Banning fault and not the San Andreas fault as preferred by Dibblee. The fault is vertical in this region and shows evidence of right-lateral displacement. The southeastern extension of this fault past the Salton Sea has not been definitely established, but speculation has been made that it continues into the Sand Hills region.

Faults of the San Jacinto zone, which includes the faults of the Superstition Mountains, are parallel to the Mission Creek-Banning fault but the zone is much more complex. The faults are vertical, and prominent scarps are visible (Dibblee, 1954). Continuity of the San Jacinto fault zone into Baja California has not been definitely established, but the fault trace continuing southeasterly into the head of the Gulf of California (see Figure 2) appears to be aligned with the San Jacinto fault zone to the north, as was first pointed out by Kniffen (1932). Evidence of Recent movement on faults of the San Jacinto zone includes fault scarps in the alluvium, earthquake epicenters, hot springs and mud volcanoes. Northwest of the area of this study, offset stream channels testify to a recent history of right-lateral displacement along the San Jacinto fault.

The third major fault zone in the region is the Elsinore fault zone. The Vallecito-Fish Creek Mountains and the Coyote Mountains were elevated along this complex fault zone and the Elsinore fault forms the southwest margin of this fault zone (Dibblee, 1954). The Laguna Salada fault, on the western side of the Sierra de los Cucapas, appears to be the southern continuation of the Elsinore fault. Fresh scarps, evidence of movement in Recent time, are visible on the Laguna Salada fault, but the very striking fault on the east side of the Cucapas surprisingly does not show any physiographic evidence for Recent movement. This fault is herewith named the Cucapa fault.

The linear and continuous eastern face of the Sierra Juárez was recognized as a fault scarp by Lindgren (1888) but evidence for Recent movement on this fault is not abundant (Allen *et al.*, 1960).

Many investigations have been made of the 1940 displacement on the Imperial fault (Ulrich, 1941; Buwalda and Richter, 1941). All evidence points to right-lateral movement with little or no vertical displacement. A maximum displacement of 19 feet (right-hand strike-slip) was measured by Richter (1958, p. 491).

Subsurface Well Data

Many wells have been drilled near the Salton Sea in the Imperial carbon dioxide gas field. However, since these wells seldom exceeded 1500 feet in depth they provide little information on the depth to the basement. (Basement is herewith defined as the igneous and/or metamorphic rocks of mid-Cretaceous age and older that form the bedrock of the area). All of the information on the well depths were taken from reports of the California Division of Mines and the daily Munger Oilogram. The useful available well data are summarized in Table 1, and the locations of the wells are shown on Plate 1. The basement depths will be used as control points for the gravity and seismic refraction data.

TABLE 1. WELLS DRILLED IN IMPERIAL VALLEY REGION

T.	R.	Sec	Name of Company and Well	Total Depth (feet)	Geology at Bottom
11S	9E	27	Standard Oil Co.; So. Land Co. 1	4531	Basement
11S	10E	31	Texas Co.; Pure (NCT-1) 1	4314	Miocene
12S	13E	4	Transcontinental Power; Sinclair	2368	
12S	13E	10	Kent Imperial Oil Co.; Sinclair 1	4720	Miocene
12S	13E	24	Sardi Oil Co.; Sardi	5618	Miocene
13S	14E	9	Amerada Petroleum Corp.; Veysey 1	8350	Miocene (?)
13S	17E	2	Ajax Oil Co.; Phyllis	2804	Basement
14S	12E	4	Texas Co.; Brawley Unit - Stipek 1	8648	L. Pliocene
16S	11E	32	Yuha Oil Co.; Yuha Well	1363	Miocene (?)
16S	12E	6	Texas Co., F. D. Browne 1	7806	Granite
16S	14E	28	Amerada Petroleum Corp.; Timken 1	7323	Miocene (?)
16S	16E	8	Texas Co.; Grupe - Engebretson 1	12,313	Pliocene (?)
16S	17E	16	Border Oil and Gas; Schafer	8015	Miocene (?)
17S	11E	20	Clarence Harrison; Yuha	2689	
17S	14E	18	Texas Co.; Jacobs (NCT-1) 1	7505	Basement
10S	24W	24	Colo. Basin Assoc. Inc.; Federal 1	6016	Top of Imperial fm. at 3010 feet

SEISMICITY

A valuable addition to the information concerning the tectonic framework of the northern part of the Gulf of California structural province including the Colorado Delta region is that provided by earthquakes. Earthquakes of magnitude 4.5 or greater on the Richter scale have been plotted on Figure 3 for the period of 1904 through March 1960. Earthquakes prior to 1934 have been taken from Gutenberg and Richter (1949). The epicenters from 1934 to 1960 were taken from the local bulletins of the Seismological Laboratory in Pasadena. A magnitude of 4.5 was selected as a lower limit not because data are unavailable for smaller size shocks but to avoid cluttering the map. Furthermore, epicenters are in general more precisely located the greater the magnitude of the shock.

The epicenters selected are probably incomplete in themselves, but all shocks were used for which epicenters were determined by the Seismological Laboratory. In referring to the map it should be kept in mind that epicenter locations in Mexico are in general poor because all of the seismograph stations of the Southern California network are in the same general azimuth to shocks south of the international boundary. Some of the epicenters in Baja California may be in error by as much as 10 miles so that caution must be used before visualizing any 'trend'. The epicenters north of the international boundary are in general much better located and with the addition of more favorably located stations in recent years, some epicenters are located within 5 km.

An examination of Figure 3 reveals the dominant northwest grain or trend of earthquake epicenters in the region marking the overall trend of the San Andreas fault zone. Also shown in Figure 3 are the locations of the known faults in the region evidenced either on the ground from geologic features or from aerial photographs.

By far the greatest seismic activity of the region, at least in the past 60 years, appears to have been along the San Jacinto fault system. Even with the lack of control on the location of earthquake epicenters in this region it is hardly conceivable that this predominance of epicenters along the San Jacinto fault would be due to consistent errors in epicenter location. The lack of epicenters along the apparent continuation of the San Andreas fault (Mission Creek-Banning fault) leads one to speculate whether this major fault has just been accumulating stress over the past 60 years or is truly now relatively inactive.

Fault plane solutions of earthquakes in this region are not available because of the lack of shocks of sufficient magnitude in recent years which would allow the use of a world wide network of seismograph stations.

The most widely publicised earthquake in the Colorado Delta region was the 1940 shock described by Ulrich (1941) and Buwalda and Richter (1941). The fault had a recognisable trace on the ground for a distance of 40 miles. The published magnitude of this shock is 6.7, but recent revision gives 7.1 as a more appropriate value (Richter, 1958, p.489). Traces of the fault are still recognisable today in some areas, and the writer visited the railroad station in Cucapa, Baja California, in December, 1960, where an 8 foot horizontal right-lateral offset was still in the telephone pole line.

Other large and damaging earthquakes in the delta region occurred in June, 1915, and November, 1915, which were attributed to movement along the San Jacinto fault (Beal, 1915; Anonymous, 1916). These shocks were assigned magnitudes of 6¼ and 7.1, respectively (Richter, 1958, p. 469). In December, 1934, a shock of magnitude 7.1 having its epicenter in the Laguna Salada area (Wood and Heck, 1951; Sykes, 1937, Plate 5) caused extensive damage in the delta region.

GEOPHYSICAL SURVEY

General Statement

The earliest published geophysical investigation in the Colorado Delta region is the magnetometer measurement of the Salton volcanic domes by Kelley and Soske (1936). Duerksen (1949) reported on pendulum gravity measurements at Niland, California, El Centro, California, and Yuma, Arizona. Tests of an airborne gravity meter were made in the Imperial Valley region by Nettleton et al. (1960) and the gravity data were compared to a free air gravity map based on sparse gravity data of G. P. Woollard. A reconnaissance gravity line made by the author in 1959 across the delta region at the latitude of the international boundary showed a steep gravity gradient associated with the eastern front of the Peninsular Ranges and led to the speculation that a combined gravity and seismic study would yield valuable information on the structural framework of the delta region and, in addition, would give information on sedimentary thicknesses.

Since much of the delta region is in Mexico, it was necessary to extend the gravity observations south of the international boundary. With the cooperation of the Institute of Geophysics of the University of Mexico approximately 400 gravity observations were taken in Baja California in the summers of 1960 and 1961.

The seismic refraction work was done in the spring of 1961 in the Imperial Valley region by the Seismological Laboratory of the California Institute of Technology.

Seismic Field Work and Reduction of Data

Eight seismic refraction profiles were obtained in the Imperial Valley region (see Plate 1 for locations). A method of refraction profiling was used which gives a rapid reconnaissance measurement of the seismic section. The method used was to keep the geophone spread fixed and to move the shotpoint away from the spread. The apparent velocity of a refracted arrival across the spread is then compared with the velocity of the arrival between the shotpoint and the first geophone interchanged. This method of refraction shooting gives true reversal information provided there are no dip reversals or complicated structures between the shotpoint and geophone spread. A dipping bed is recognized by an en echelon pattern or "shingling" of arrivals on the time-distance graph.

A contract drilling crew was used to drill shot holes to an average depth of 60 feet. However, it was found, particularly on the east side of the Imperial Valley, that excellent seismic records could be obtained with small charges placed in hand drilled holes 5 feet below the surface. In this region, when shooting near canals, the water table was about 5-6 feet below the surface in sandy material, and excellent energy coupling was obtained. The size of the charge used was extremely variable but it was generally found for shot to detector distances greater than about 6 miles that 30-50 lbs. of Vibrogel 3 were necessary. On the average, the maximum depth penetrated was about 0.3 to 0.4 times the horizontal distance between shotpoint and geophone spread.

The raw travel times were first corrected for the depth of the shot by correcting the raw travel times so that the shotpoint was moved back to the surface. Because of the relatively flat terrain along the refraction profiles, the shot and detector were then effectively at the same elevation. This correction is sufficient for a reconnaissance refraction profile. Conventional intercept time methods were then used on the time-distance curves to determine velocities and layer thicknesses.

Seismic Refraction Profiles

The location of the seismic profiles is shown on the accompanying gravity map (Plate 1). The seismic results are summarized in Table 2. Sample seismograms from Profile 6 are shown in Figure 4. Figures 5 to 10 show the travel time graphs and deduced seismic sections.

PROFILE 1 (Fig. 5): This profile was shot along the Ogilby-Glamis road on the east side of the Sand Hills (Algodones Dunes). The depth to basement is about 2200 feet. The 6970 ft/sec layer gave a very strong arrival on the seismograms which persisted as a strong second arrival. The absence of sedimentary velocities greater than 6970 ft/sec probably indicates that a substantial portion of the Cenozoic section present elsewhere in the valley is absent in this region.

PROFILE 2 (Fig. 6): This profile was shot along the Coachella Canal on the west side of the Sand Hills. The depth to basement is about 9370 feet. Below the 6270 ft/sec layer are three layers with velocities of 7300 ft/sec, 8770 ft/sec and 11,050 ft/sec within the Cenozoic section. An alternate interpretation would be to combine the 7300 ft/sec layer with the 8770 ft/sec layer. However, this interpretation gives an almost identical depth to basement as that determined with the 7300 ft/sec layer present. A comparison of the basement depths between

TABLE 2. VELOCITIES AND LAYER THICKNESSES

Profile	V_0	V_1	V_2	V_3	V_4	V_5	V_6
1	3720		6970				18,520
2	2270	6270	7300	8770	11,050		20,000
3	1200	5750	7620	8580	12,500		18,180
4W	1790	5650	6900	8400	11,830		
8E							
5E	1500	6070	7580	8520	11,930	15,475	
6W							
7	(1500)		6944				19,230

	h_0	h_1	h_2	h_3	h_4	h_{total}
1	407		1790			2197
2	77	1315	1450	2460	4070	9372
3	40	1426	3184	855	4645	10,150
4W	98	593	1029	3366		5086
8E	33	593	1543	3748		5917
5E	67	1520	1570	3935	4785	11,877
6W	32	1674	1770	3842	4222	11,540
7	134		2620			2754

V is velocity in ft/sec; h is layer thickness in feet

E and W signify East or West end of reversed profile;

( ) denotes assumed velocity.

profiles 1 and 2 shows the rapid deepening of basement across the Sand Hills.

PROFILE 3 (Fig. 7): This north-south profile is located along the East Highline Canal on the east margin of the cultivated area of the Imperial Valley. Below the weathered layer the arrivals show layers with velocities of 5750 ft/sec, 7620 ft/sec, 8580 ft/sec and 12,500 ft/sec. The 8580 ft/sec arrival was not present as a first arrival. The velocity of 8580 ft/sec is only an average apparent velocity since the first motion was very difficult to determine on this second arrival. Furthermore, a slight "shingling" of the arrivals indicates a southerly dip of this layer. Neglecting the presence of the 8580 ft/sec layer has only a negligible effect on the calculated depth to basement. Because of the importance of obtaining an accurate measurement of the depth to the basement, this profile was shot to a distance of over 44,000 feet to be certain that the 18,000 ft/sec arrival was definitely a basement arrival. The depth to basement is 10,050 feet. Very strong second arrivals having an apparent velocity of 7620 ft/sec are also present and are shown on the travel-time graph. Since this second arrival has twice the intercept time of the 7620 ft/sec layer as a first arrival, it is identified as a double refraction of the 7620 ft/sec layer.

The Texas Company "Grupe-Engebretson" well, located south of Holtville, California (Plate 1), was velocity surveyed to 7827 feet. This well had a surface velocity of about 1000 ft/sec and then 'broke' into a 5230 ft/sec layer. The interval velocities ranged from 6580 ft/sec to 15,625 ft/sec and two small velocity reversals with depth were found. A velocity-depth function of $V = 5777 + 0.652D$ was determined from the interval velocity log. Using this velocity-depth function a refraction travel time curve can be computed from the relation $T = \frac{2}{0.652} \sinh^{-1}\left[\frac{0.652\,X}{2(5777)}\right]$ where T is the time in seconds and X is the source to detector distance in feet (Dix, 1952, p. 248). This computed travel time curve is shown for comparison in Figure 7. The refraction data agree well to a depth of 5500 feet but then deviate strongly at the 12,500 ft/sec layer from this computed travel-time curve based on a linear increase of velocity with depth. However, it should be pointed out that the Grupe-Engebretson well is located about 3 miles southeast of this profile and that a 12,500 ft/sec velocity was not identified in the well velocity survey. From 2800 feet to the bottom of the Grupe-Engebretson well were various rock types, all reportedly belonging to the Borrego formation. Since the wide range of velocities measured in this well was thought to be entirely within this formation it would not be profitable to attempt to assign stratigraphic horizons to the velocity discontinuities revealed by the refraction measurements. Furthermore, a wide range of velocities is often determined for similar rock types, and similar velocities are often determined for widely different lithologies. However, the abrupt velocity change to 12,500 ft/sec indicated from the refraction data may be related to sediments of some stratigraphic significance that were not penetrated in the Grupe-Engebretson well.

PROFILES 5E & 6W (Fig. 8): These two east-west profiles form one completely reversed refraction profile. This profile is located directly south of Profile 3 about ½ mile north of the international boundary. The average velocities measured are 6070 ft/sec, 7580 ft/sec, 8520 ft/sec, 11,930 ft/sec and 15,475 ft/sec, with almost negligible dip indicated for the refracting horizons. Strong second arrivals were present on many of the seismograms but all were identified as double refractions. The total length of this refraction line was about 8.5 miles yet only a velocity of 15,475 ft/sec was reached. The depth to the 15,475 ft/sec layer is about 11,600 feet. An interesting question is immediately posed whether this 15,475 ft/sec arrival is a basement arrival. It is not believed that this is an arrival from the basement since 15,475 ft/sec is low compared to the 18,000 ft/sec to 20,000 ft/sec basement velocity measured elsewhere in the delta region. Assuming that the basement velocity is 18,000 ft/sec and that the velocity immediately 'breaks' into a basement arrival at the most distant point on the travel time graph, the minimum depth to basement is about 15,400 feet under this profile.

PROFILE 7 (Fig. 9): This north-south profile was shot along the right of way of the private railroad of the Portland Cement Co. Because of field difficulties, no near-spread shots were fired so a surface layer of velocity 1500 ft/sec was assumed to account for the failure of the 6944 ft/sec layer to have a zero intercept. The depth to basement is about 2750 feet. The offset in the basement arrival is interpreted as an uplifted fault block in the basement or a small basement high. The approximate vertical displacement, Z, may be computed from the relation $Z = \frac{\Delta t V_1 V_2}{(V_2^2 - V_1^2)^{1/2}}$ (Nettleton, 1940, p.273). With $\Delta t \cong 0.08$ sec, $V_1 = 6944$ ft/sec, and $V_2 = 19{,}230$ ft/sec, Z is approximately 600 feet. A small gravity high of about 5 mgals is found over this basement high.

PROFILES 8E & 4W (Fig. 10): These two east-west profiles form one partially reversed refraction profile in the Superstition Hills area. Because of the sloping terrain between the shotpoints and the detector, all travel times were reduced to a datum of 100 feet below sea level using a technique described in Nettleton (1940, p. 301). This correction reduced the observed travel times as if the surface low velocity (1790 ft/sec) layer were not present. In the absence of observed data, a 6900 ft/sec arrival was assumed in the west to east direction (see Fig. 10).

Beneath the unconsolidated surface sediments, average velocities of 5650 ft/sec, 6900 ft/sec, 8400 ft/sec and 11,830 ft/sec were measured. Approximately a 1-2 degree easterly dip is indicated for the refracting horizons. However, this is only an apparent dip in the direction of the profile and it is quite possible that the true dip may be greater than that indicated here. Exceptional efforts were made to obtain basement arrivals by extending this refraction line to 44,000 feet (8.5 miles). Charges were placed at a depth of 60 feet in the basement complex of the Superstition Mountains, located 44,000 feet west of the geophone spread. Even though large charges were fired (50 lbs), no detectable arrivals were received at the geophone spread. However, these charges were fired close to the Superstition Mountain fault and it is possible that the energy transmission was complicated by the presence of this fault. If we assume that the basement velocity is 18,000 ft/sec and that the velocity immediately breaks into a basement arrival at the most distant arrival on the 12,300 ft/sec layer, it can be stated that the <u>minimum</u> depth to basement is about 11,500 feet under this profile.

An examination of the time-distance graph shows that in crossing the Superstition Hills fault no large offsets in the travel time data are observed. Thus, it appears that large vertical displacement is not present on the Superstition Hills fault in this region. Nevertheless, this does not preclude vertical displacements of 100-200 feet, which would be difficult to detect by reconnaissance refraction surveying.

Gravity Field Work and Reduction of Data

Approximately 750 gravity observations were taken in the United States and Mexico with a Worden gravimeter. In addition, approximately 400 gravity stations were kindly furnished by Standard Oil Company of California. The gravity observations are tied to a network of gravimeter base stations in the Imperial Valley which by a succession of stations are tied to the USCGS pendulum station in Pomona, California (Duerksen, 1949). Loop ties were made every 2-3 hours to determine the combined tidal and instrument drift. Elevations of stations in the United States were obtained from bench marks of the United States Geological Survey and the United States Bureau of Reclamation, level survey lines, and a few stations by altimeter. In Mexico gravimeter base stations were established on bench marks of the International Boundary and Water Commission. The elevations of the remainder of the gravity stations in Mexico were determined by altimeter. The possible elevation error in Mexico is estimated to be 15 feet. Horizontal location of the gravity stations in the United States is probably within 50 feet; in Mexico because of the inadequate maps available, some of the remote stations in the Laguna Salada area may conceivably be in error by as much as 1000 feet of horizontal distance. However, the majority of the stations in Mexico are probably located to within 500 feet of horizontal distance. The gravity observations were corrected for drift, elevation and latitude using conventional techniques. Considering all these factors, the precision of the gravity observations in the United States is estimated to be 0.2 mgal, whereas in Mexico the precision is estimated to be 1 mgal, although some stations could be in error by more than 1 mgal.

An elevation factor of 0.069 mgal/foot was used corresponding to a rock density of 2.0 gm/cc. This is the average density of the surficial alluvium in the delta region. For stations above 1000 feet elevation on basement in the Peninsular Ranges an elevation factor of 0.060 mgals/foot was used, corresponding to a rock density of 2.67 gm/cc. In the United States, terrain corrections were made out through zone H (8,578 feet) using the terrain correction tables of Hammer (1939). Trail terrain corrections for a few stations were carried out through zone M (71,996 feet) but these corrections did not significantly alter the gravity picture. Terrain corrections were not made for the gravity stations in Mexico because of the lack of topographic maps. Since most of the stations in Mexico are in the broad alluviated delta region, failure to make terrain corrections does not have a significant effect on the majority of the stations. Near the Sierra de los Cucapas failure to make terrain corrections could conceivably introduce errors of as much as 3 mgals. The Bouguer anomaly values for stations near the Cucapas would be raised relative to the values of the stations located in the relatively level alluviated areas.

Gravity values were reduced to the complete Bouguer anomaly with respect to the International Ellipsoid. 1000 mgals were added to the gravity values so that the gravity contours on the map are all positive.

Density

A number of outcrop samples were collected in the Imperial and Coachella Valley region by the Standard Oil Company of California. Bulk dry densities of the pre-Tertiary plutonic and metamorphic rocks ranged from 2.58 gm/cc to 2.79 gm/cc. 18 samples were measured; the average density was 2.67 gm/cc. Saturated bulk densities (the density of rock filled with water, which is the probable condition of most deeply buried rocks) were also determined for 31 samples of the pre-Tertiary rocks. Densities ranged from 2.40 gm/cc to 2.81 gm/cc; the average density was 2.67 gm/cc. Representative samples of the plutonic and metamorphic rocks of the Sierra de los Cucapas were collected by the author. 7 samples were measured; the densities ranged from 2.61 gm/cc to 2.80 gm/cc, with a mean bulk dry density of 2.70 gm/cc. Samples of the plutonic rocks of the Peninsular Ranges were also collected by the author. Bulk dry densities of 7 samples from the La Posta pluton ranged from 2.64 gm/cc to 2.66 gm/cc. Samples of the various plutonic rocks adjacent to the La Posta pluton were collected from four different localities and ranged in density from 2.70 gm/cc to 2.82 gm/cc.

For the extremely heterogeneous Cenozoic sedimentary rocks saturated bulk densities were determined. Samples ranged in density from 1.85 gm/cc for a claystone of the Imperial formation to 2.57 gm/cc for a sandstone of the Borrego formation. 23 samples were measured; the mean density was 2.33 gm/cc.

Some volcanic flows are found within the Cenozoic deposits, particularly on the west side of the Imperial Valley. Densities ranged from 2.32 gm/cc for a Pleistocene obsidian from the Salton Volcanic domes to 2.61 gm/cc for a lava sample from the Alverson Canyon formation on the southwest margin of the Imperial Valley. Samples were also collected from Cerro Prieto, the large volcanic cone south of Mexicali. The andesitic flow or ejecta samples collected showed an average bulk dry density of 1.94 gm/cc.

Saturated bulk density measurements were also made on samples from several wells in the delta region. An overall general increase of density with depth was measured although density reversals were present within the Borrego formation. In the Texas Company "Grupe-Engebretson" well densities ranged from 2.06 gm/cc to 2.59 gm/cc.

For purposes of interpretation, a representative density of 2.67 gm/cc is given to the pre-Tertiary rocks. Because of the extreme heterogeneity of the Cenozoic sedimentary deposits it is very difficult to assign a representative density to these deposits. Because it is recognized that densities determined from surface outcrop samples can be misleading and fail to take into account probable compaction of the sediments with depth, a mean density of 2.40 gm/cc is assigned to the Cenozoic deposits for purposes of interpretation in areas where no other control exists.

However, it is recognized that the density contrast may vary from -0.4 gm/cc to -0.2 gm/cc owing to the variability of the densities of the Cenozoic deposits, known density reversals with depth within the Borrego formation, and a general increase of density with depth. Between these extreme density contrasts, depths to basement may actually vary from 70 per cent to 140 per cent from that computed on the basis of the gravity data alone. On the profiles analyzed here, where the gravity anomalies can be 'anchored' to control points such as wells or seismic refraction lines so that a fairly accurate appraisal of the density contrast can be made, the calculated depths based on gravity probably range from 80 per cent to 130 per cent of the true depth.

Gravity Contour Map

The Bouguer gravity data are presented in Plates 1 and 2. The gravity data for the delta region in the United States are shown in Plate 1; Plate 2 gives the gravity data for the region south of the international boundary.

A casual inspection of the Bouguer gravity field shows that the overall trend of the isogal contours is northwesterly, in agreement with the overall trend of the tectonic features in the region. The Bouguer gravity ranges from 990 mgals to 920 mgals. (Since 1000 mgals were added to the final Bouguer gravity values, all gravity values are actually negative with respect to the International Ellipsoid.)

Since the gravity values on basement outcrops at Signal Mountain, the Superstition Mountains and Pilot Knob are approximately equal, this suggests that the east-west regional gradient is zero within the area bordered by these basement outcrops. However, approaching the plutonic rocks of the Peninsular Ranges, to the west of the delta region, the gravitational field becomes systematically more negative. In fact, the eastern front of the Peninsular Ranges shows a negative Bouguer anomaly compared with the alluviated delta region to the east. This negative gravity anomaly will be discussed later under gravity profile A-A', which is a 190 mile east-west gravity profile from San Diego, California to Yuma, Arizona.

A very pronounced gravity minimum is associated with Laguna Salada. Because of inaccessibility and location difficulties, the shape of this anomaly is not well defined. Quite possibly, south of Demara's Well even lower gravity values could be found. The measured gravity relief from the minimum value in Laguna Salada to the Sierra de los Cucapas is about 65 mgals. From a simple computation using the formula for the gravitational attraction of an infinite horizontal sheet and a density contrast of -0.27 gm/cc, a rough depth of 19,000 feet is indicated for the Laguna Salada basin. Since the density of the sediments in Laguna Salada varies with depth in an unknown manner, a refinement of the computation is not justified.

South of Sierra del Mayor, on the highway to San Felipe, the Bouguer gravity values drop off sharply by about 10 mgals/mile crossing Laguna Salada and rise sharply by about 10 mgals/mile approaching the Sierra Pinta, at the southern end of the map. These steep gradients undoubtedly reflect bounding vertical faults along which the Cenozoic sediments of Laguna Salada and the pre-Tertiary rocks of the Sierra del Mayor and the Sierra Pinta are in fault contact (see gravity profile D-D').

By far the dominant feature of the Bouguer gravity field in Mexico (Plate 2) is the steep gravity gradient present on the west side of the Sierra de los Cucapas. Even though the number of gravity stations is small in the region and the gravity stations are not precisely located, there is no doubt that this steep gradient exists. This steep gradient is undoubtedly associated with the Laguna Salada fault, located on the west side of the Cucapas. From the indicated steepness of this gravity gradient (7 mgals/mile), the interface between the sediments of Laguna Salada and the basement rocks of the Cucapas is probably vertical or dips steeply towards the center of Laguna Salada. This zone of steep gravity gradient, which roughly parallels the Laguna Salada fault, can be followed into the United States (Plate 1) to the Elsinore fault. Thus, it is believed on the basis of this gravity gradient that the Laguna Salada fault is the southern continuation of the Elsinore fault.

A large gravity minimum is present in the Lower Borrego Valley-San Felipe Creek area (Plate 1). The Standard Oil Company "Southern Land Co. 1" well (Table 1) was drilled about 4 miles north of this gravity minimum and bottomed in basement at a depth of 4531 feet. The amplitude of this gravity minimum with respect to the Southern Land Co. well is about -13 mgals. Samples from this well, in the depth range of 1900 feet to 4462 feet, ranged in density from 2.42 gm/cc to 2.66 gm/cc. Using this basement depth and -0.2 gm/cc as the average density contrast between the sediments and basement, and treating the mass of sediments as an infinite slab, a depth of 9600 feet is indicated for the Lower Borrego Valley. Of course, this determined depth is only valid provided this gravity minimum can be entirely attributed to a thickening of the sediments. A small error is made by treating the mass of the sediments as an infinite slab, and this approximation tends to underestimate the thickness of the sediments.

Toward the center of the Imperial Valley the Bouguer gravity averages about -12 mgals to -20 mgals relative to bedrock areas at the Superstition Mountains and Signal Mountain. It is difficult to reconcile these Bouguer gravity values with sedimentary thicknesses alone using calculations with a single sediment-basement density contrast. Regardless of what density contrast is selected within the broad range of -0.2 gm/cc to -0.5 gm/cc, an erroneous basement depth is obtained. For example, the gravity relief between Signal Mountain and seismic profiles 5 & 6, along the Mexican border, is about 22 mgals. If we estimate the basement depth using this local anomaly and a contrast of -0.2 gm/cc, we obtain 8500 feet as the thickness of sediments, yet seismic profile 5 indicates a minimum depth to basement of 15,400 feet. Density samples of the sediments from the nearby Grupe-Engebretson well showed a density of 2.50 gm/cc at a depth of 7000 feet and a density of 2.59 gm/cc at a depth of about 11,300 feet. We are thus led to believe that the observed Bouguer gravity in the center of the basin is seeing density contrasts within the Tertiary section, rather than seeing only a sediment-basement density contrast. This result is not unexpected in deep and large sedimentary basins where there is an increase of density with depth within the sedimentary column because of compaction, so that the deeper sediments have in situ densities very close to basement densities (Vyskočil, 1956).

Superposed upon this Bouguer gravity field are almost certainly the effects of lateral density variations within the pre-Tertiary basement rocks. Near Brawley, California, are two fairly symmetrical gravity maxima. Since the Bouguer gravity at these maxima is only -10 mgals to -15 mgals relative to bedrock areas at the Superstition Mountains and Signal Mountain, it is again difficult to explain these anomalies by a thickening of the sediments alone. If we assume that the larger gravity maximum, east of Brawley, is caused only by the gravity effect of a simple geometric form such as a sphere, we can estimate the depth to the center of the anomalous mass. From the width of this 8 mgal anomaly at half amplitude the depth to the center of the anomalous mass is found to be 22,000 feet. Since seismic profile 3 on the east flank of this gravity maximum indicated a basement depth of 10,000 feet, we can conclude that density variations within the basement are contributing to the observed gravity in this region. This does not preclude relief on the basement floor contributing to these observed gravity maxima, but it is difficult to explain these anomalies solely on the basis of basement relief. In the absence of magnetic data which would yield information on variations within the basement rocks, a further analysis is not justified.

A zone of gravity gradient of about 4-5 mgals/mile is present where the Superstition Hills fault and Superstition Mountain fault appear to join to the northwest if one would visually extend their fault traces in this direction. It is believed that this gradient suggests the northwesterly convergence of these two faults. However, it is difficult to say, on the basis of gravity data alone, whether these faults represent the southern continuation of the San Jacinto fault to the north. The surficial trace of the San Jacinto fault is lost beneath the alluvium of the Lower Borrego Valley and the isogal contours in this region reflect an oval shaped sedimentary basin rather than defining a gradient zone for a discrete single fault. Nevertheless, if the San Jacinto fault were present in this region, buried beneath thousands of feet of sediments and with little vertical displacement, it is improbable that a fault could be recognized by gravity methods alone. The seismicity map (Figure 3) shows several earthquake epicenters in this region; therefore, for lack of better evidence, it is believed that the Superstition Mountain fault and the Superstition Hills fault represent the southern continuation of the San Jacinto fault zone, which is probably 4-6 miles wide in this region.

West of El Centro is a large gravity minimum which can be interpreted as caused by a thickening of the Cenozoic sediments in the Seeley Basin (see gravity profile B-B'). The isogal contours defining this local minimum are bent or 'kinked' in the vicinity of El Centro along the projected strikes of the Superstition Hills fault and the Superstition Mountain fault. This distortion of the gravitational field indicates that these two faults continue at least as far south as Heber, California, and probably converge into one fault as their projected strikes would indicate.

On the northeast side of the Sierra de los Cucapas (Plate 2) is a northwestward trending zone characterized by a fairly steep gravity gradient. This gravity gradient is a reflection of the rapid rise of the basement towards the Cucapas. It is believed that this entire rapid rise of basement is a reflection of the San Jacinto fault zone which, if projected from the northwest, would pass through this gravity gradient zone. However, it is not possible to identify individual fault breaks within the fault zone in this region. The Bouguer gravity maximum and the steep gradients associated with the Cucapas show that this mountain range is uncompensated.

It has been speculated that a major northwest-southeast trending fault is present beneath the Sand Hills which represents either the direct continuation of the Mission Creek-Banning fault (San Andreas) from the north or is offset en échelon from this fault. An examination of the gravity map in this region shows that the total gravity relief across the Sand Hills is not large. The gravity relief across the Sand Hills along the Brawley-Glamis road is about 6-7 mgals, between seismic profiles 1 and 2 about 6 mgals, and along U. S. Highway 80 about 8 mgals. These facts suggest that if a major fault is present in this region, at least no major vertical displacement is evident. North of the present area of investigation the gravity gradient crossing the Mission Creek-Banning fault is about 8 mgals/mile.

Recognition of a buried fault which is predominantly strike-slip will, of course, be difficult by gravity methods alone. Two seismic refraction profiles (1 & 2) were shot on opposite sides of the Sand Hills and indicate a deepening of the basement by about 7000 feet across the Sand Hills. Assuming a sediment-basement density contrast of -0.2 gm/cc, a 7000 feet deepening of the basement across the Sand Hills should produce about an 18 mgal anomaly. A density contrast of -0.1 gm/cc would produce about a 9 mgal anomaly. Thus, we are forced to conclude that the mean sediment-basement density contrast across the Sand Hills is abnormally low, that there is a density change across the Sand Hills contributing to the observed gravity, or that the basement depths determined by the refraction measurements are incorrect. We shall examine these possibilities in greater detail under gravity profile E-E'.

In the vicinity of Yuma, Arizona, are two very pronounced gravity maxima. The gravity maximum west of Yuma corresponds with the basement outcrop of Pilot Knob. In the gravity maximum south of Yuma the Bouguer gravity attains the maximum value for the delta region. Even though no outcrops of basement are found near this gravity maximum, it is believed that this anomaly is a reflection of a very shallow basement south of Yuma. Early in 1920, a diamond drill hole was drilled by the Yuma Basin Oil and Refining Co., 5 miles south of Yuma, which encountered granite at 730 feet (Butler and Allen, 1921). Pilot Knob and this shallow basement near Yuma define the eastern limit of the Gulf of California structural trough in this region.

Machine Computation Methods

Selected gravity profiles were analyzed using two computational techniques programmed for the Bendix G-15D digital computer. One technique was to compute the gravitational attraction of any irregular polygonal shaped two-dimensional body using a method of line integration described earlier by Talwani et al. (1960). By varying the shape of the two-dimensional body an attempt was made to match the computed anomaly to the observed regionally corrected gravity anomaly. To achieve the maximum accuracy possible, gravity profiles were selected for which the observed gravity anomaly could be anchored to well depths, basement depths determined from the seismic lines, or basement outcrops. Since one of the primary interests was the thickness of the sedimentary rocks in the delta region, anchoring the observed gravity anomaly to known depths enables one to make an approximate determination of the density contrast between the sedimentary and basement rocks. This method of direct integration was found to be a satisfactory computational technique and permits the total gravitational attraction to be built up from several contributing masses of different densities. However, even with the speed of a digital computer the method is tedious since variations in the shape of the two-dimensional body must be constantly re-entered into the computer until the computed anomaly satisfactorily agrees with the observed anomaly.

The second computational technique was a method of automatic interpretation described by Bott (1960) and programmed for the Bendix G-15D by Healy (1961). This method is particularly applicable when a gravity anomaly can be entirely attributed to a sedimentary basin for which the density contrast between the sediments and basement rocks is fairly well known. The anomalous body is approximated by narrow two-dimensional rectangles. After the observed regionally corrected gravity anomaly is entered into the computer, the calculated anomaly is matched to the observed anomaly by an iterative trial and error procedure. The depth of the narrow rectangles is constantly changed until the theoretical anomaly agrees with the observed anomaly to the desired precision.

Selected Gravity Profiles

Profile A-A': Figure 11 shows the observed Bouguer gravity for a 190 mile section along U.S. Highway 80 from 5 miles east of Yuma, Arizona, to San Diego, California. This east-west profile crosses both the Imperial Valley province and the Peninsular Ranges. The Bouguer gravity is about -20 mgals in the Yuma area, near basement outcrops at Pilot Knob, and drops off to an average value of -40 mgals on the valley floor. Using Woollard's empirical curve (1959) relating Bouguer anomaly to crustal thickness, a -40 mgal anomaly yields a crustal thickness of 35 km for the delta region. If we use the empirical curve relating surface elevation to crustal thickness, a mean elevation of 0 km for the delta region yields a crustal thickness of 32 km. Since there is a thick layer of low density sediments present in this region, the Bouguer anomaly values have probably incorporated this geologic contribution which, in general, gives an over-estimate of crustal thickness. For this reason, it is felt that 32 km is probably a better estimate of crustal thickness for the delta region. However, it cannot be too strongly emphasized that without crustal refraction data for anchor points it is not possible to determine from the observed Bouguer anomaly values what crustal thickness and structure actually is present. The final answer must wait for seismic data.

West of Plaster City the observed gravity gradient is about 4 mgals/mile. At this point, U.S. Highway 80 crosses perpendicular to the strike of the projected trace of the Elsinore fault (see Plate 1). It thus appears, on the basis of this steep gravity gradient and the general trend of the isogal contours in this region, that good evidence is presented for establishing the continuity of the Elsinore fault to the Laguna Salada fault.

By far the dominant feature of the gravity profile is the sharp negative anomaly associated with the Peninsular Ranges. Between Pine Valley and the Jacumba area the Bouguer gravity drops off sharply to a value of about -80 mgals. The observed gradient to this gravity minimum is about 2-3 mgals/mile. It should be pointed out that this is only the gravity gradient as observed along U.S. Highway 80. It is quite probable that these gravity observations were not taken in the direction of maximum gradient so that the maximum gradient may actually be greater than that indicated here.

Let us first assume that this negative anomaly is due to local crustal thickening under the Peninsular Ranges. Assuming a crust-mantle density contrast of -0.45 gm/cc, a "step" in the Mohorovicic discontinuity from 35 km to 45 km would only produce a maximum gravity gradient of about 1.5 mgals/mile. Therefore, reasonable crustal thickening alone cannot account for this sharp negative anomaly. Press (1956), using phase velocity data from Rayleigh waves, determined a normal continental thickness under the Peninsular Ranges. An unreversed refraction line from Corona, California, south to the Mexican border indicated a depth to the Mohorovicic discontinuity under the Peninsular Ranges of about 30 km (Shor and Raitt, 1958). S. Alexander (1961, personal communication) using phase velocity data in the triangle with corners at Palos Verdes, Mt. Palomar and Barrett determined a crustal thickness of 35 km for the Peninsular Range province. We are thus forced to look for a mass deficiency higher in the crust to account for this negative anomaly. Between Pine Valley and the gravity minimum at Tecate Divide, a distance of 23 miles (37 km), the Bouguer gravity changes by about 58 mgals. Using the relation $Z < \pi^{-1} X_{max} \log \left\{ 4k\rho X_{max} / g_{max} \right\}$* derived by Bullard and Cooper (1948) we can arrive at a limit to the depth that can be assumed for the material which produces the gravity anomaly. Assuming that the anomaly is caused by a density contrast in the range of -0.25 gm/cc to -0.40 gm/cc, a maximum depth between 17 km and 22 km is indicated for the mass which produces the gravity disturbance.

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*X_{max} is distance in km between maximum and minimum value of g, ρ is density in gm/cc, k is the gravitational constant, g is the anomaly in gals, Z is the depth in km.

The association of negative anomalies with intrusive masses of silicic rock has been commonly observed (Bott, 1953; Oldham, 1958: Woollard et al. 1960) and this explanation of the gravity minimum must be considered.

The batholith of southern California, made up of many separate plutons, occupies the core of the Peninsular Ranges. An examination of the areal geologic map along U.S. Highway 80 (Gastil and Bushee, 1961) shows that this gravity minimum coincides with one particular pluton-- the La Posta quartz diorite pluton. Representative rock samples were collected along this gravity profile by the author. Bulk dry densities of samples from the La Posta pluton from seven different localities ranged from 2.64 gm/cc to 2.66 gm/cc. Various igneous and metamorphic rocks are found in contact with the La Posta pluton. Samples of these rocks collected from four different localities ranged in density from 2.70 gm/cc to 2.82 gm/cc. No density samples were collected from the gabbros but 2.90 gm/cc to 3.00 gm/cc is a reasonable density range to assume.

Even though extensive sampling was not done in this region, it is significant that samples from the La Posta pluton are less dense than samples from any of the surrounding plutons. Therefore, it is believed that this negative gravity anomaly is a result of the density contrast between the La Posta pluton and the surrounding rocks.

Shown in Figure 11 is a theoretical anomaly based on a simplified two-dimensional configuration, which is in agreement with the observed Bouguer anomaly. The gravity anomaly is anchored to the Texas Co. Browne well, which gives the depth to the sediment-basement interface on the west side of the Imperial Valley. A mean sediment-basement density contrast of -0.20 gm/cc, in agreement with density samples from the Browne well (see gravity profile B-B'), was chosen for the computations.

In the center part of the Imperial Valley we have projected into our gravity profile the Texas Co. Grupe-Engebretson well, which bottomed at 12,300 feet in sediments, and seismic profiles 5 and 6, which indicated a minimum basement depth of 15,400 feet. It is readily seen that carrying the 2.47 gm/cc-2.67 gm/cc interface, which represents basement at the Browne well, eastward into the center of the valley gives a depth which does not agree with the Grupe-Engebretson well depth nor with the minimum seismic depth to basement. Therefore, it is believed that while the 2.47 gm/cc - 2.67 gm/cc interface represents basement at the Browne well, in the center of the valley this density interface is within the Tertiary section. Therefore, in this region we have anchored our anomaly curve to a depth of 15,400 feet where we have selected 2.84 gm/cc as the basement density compatible with an 18,180 ft/sec (6 km/sec) to 20,000 ft/sec (6.6 km/sec) basement velocity measured in the center part of the delta region.

Because of probable lateral density variations within the basement and the general increase of density with depth within the sedimentary column towards the center of the depositional basin, a completely erroneous picture would be obtained by only using a one layer density contrast computation in the center of the basin. The 2.47 gm/cc - 2.67 gm/cc interface shown is meaningless in terms of defining relief on the basement floor in the center of the basin. Furthermore, the variations in the shape of the 2.47 gm/cc - 2.67 gm/cc interface are probably not real since our assumptions are oversimplified. Since our control is limited and because the extent and amount of these lateral density variations within the basement are unknown, a further refinement of our computations is not justified. However, a suggestion can be made that a possible basement density discontinuity exists crossing the San Jacinto fault zone.

At the Elsinore fault zone the structural picture is very complex causing severe edge effects on the observed gravity. The computational model shown is in fair agreement with the known geological picture (Dibblee, 1954) and the theoretical anomaly gives a fairly good fit to the observed data.

<u>Profile B-B'</u> (Fig. 12): This gravity profile is anchored to the Texas Co. Browne well which bottomed in "granite" at 7806 feet. Between basement outcrops at nearby Signal

Mountain and this well, the total gravity relief is about 19-20 mgals, so an appropriate mean density contrast of -0.20 gm/cc, in agreement with density samples from the Browne well, was selected between the Cenozoic sediments and the pre-Tertiary basement in this region. We can also approximate a gradual increase of density with depth by computing the gravity anomaly for a two-layer sediment problem. Also shown in Figure 12 is a two-layer density model, compatible with density measurements in the Browne well, which also gives a very good fit to the observed data. The indicated depth for the Seeley Basin is 12,900 feet for the one layer problem and 11,800 feet for the two-layer problem. This gravity profile crosses roughly at right angles to the projected strike of the San Jacinto fault zone from the northwest. A small step in the observed gravity is present across the apparent continuation of the San Jacinto fault zone. It is significant that a vertical displacement of about 1870 feet was necessary in both models in order to match the observed anomaly across the San Jacinto fault zone in this region. If basement density increases eastward across this fault zone, then probably a greater vertical displacement would be necessary. In view of profile A-A' which suggests density variations within the basement, the indicated basement depth shown in Figure 12, east of the San Jacinto fault zone, is probably incorrect.

<u>Profile C-C'</u> (Fig. 13): This east-west gravity profile is tied at the west end to basement at the Sierra de los Cucapas. A significant gravity gradient of about 4 mgals/mile is visible crossing the projected trace of the San Jacinto fault zone. Also shown in Figure 13 is the approximate location of a Recent fault break visible on 1935 aerial photographs of the delta region as a fault scarp in the alluvium. Under the assumed density contrast of -0.27 gm/cc a vertical displacement of about 6700 feet is indicated crossing this fault zone in this region.

<u>Profile D-D'</u> (Fig. 14): This north-south gravity profile crosses the south end of Laguna Salada and is tied to basement outcrops of the Sierra Mayor and the Sierra Pinta. Striking evidence is shown on this gravity profile that this part of Laguna Salada is a graben or down-dropped fault block between the Sierra Mayor and the Sierra Pinta. Under the assigned density contrast of -0.27 gm/cc the indicated vertical displacement on the bounding faults is about 15,000 feet.

<u>Profile E-E'</u> (Fig. 15): Figure 15 shows the observed gravity at ½ mile intervals across the Sand Hills along the Brawley-Glamis road between the Coachella Canal and Glamis. Seismic profiles 1 and 2 were shot on opposite sides of the Sand Hills, about 8 miles southeasterly from this gravity profile. Since gravity data were not obtained directly across the Sand Hills between these seismic profiles, a compromise was effected by

'projecting' the basement depths measured on to the profile along the Brawley-Glamis road. Since the seismic profiles indicated essentially no dip on the basement, projecting these depths northward probably introduces no gross error in the depth to the basement. Seismic profile 1, on the east side of the Sand Hills, indicated a depth to basement of about 2200 feet. One may argue that perhaps this seismic profile did not truly measure a basement velocity but measured a high velocity volcanic layer so that the basement depth determined is too shallow. However, the Ajax Oil Co. "Phyllis" well was drilled about 8 miles northwest of Glamis on the east flank of the Sand Hills and reached basement at a depth of 2804 feet. It is therefore felt that the seismic depth measurement is correct.

In the two-dimensional configuration shown in Figure 15, we have fixed the basement depth at 2200 feet on the east side of the Sand Hills and at 9372 feet on the west side, as measured by seismic profile 2. A first attempt was made to explain the observed anomaly using a sediment-basement contrast only. Using the basement configuration shown, with the basement depth fixed at both ends of the profile a gravity anomaly was computed for a sediment-basement contrast of -0.10 gm/cc. It is readily seen that a basement configuration using a sediment-basement contrast of about -0.1 gm/cc could presumably be computed that would give the observed

Bouguer anomaly. However, in view of the density measurements made on the Tertiary sediments it is felt that such a low contrast seems unreasonable.

Let us now assume that a strike-slip fault is present under the Sand Hills which brings into contact basement rocks of different densities. The solid curve in Figure 15 shows the computed anomaly for a sediment density of 2.37 gm/cc and basement densities of 2.74 gm/cc and 2.63 gm/cc in fault contact. The density variation in the basement was assumed to extend 10 km beneath the surface. Since the computations were made using density <u>contrasts</u> the assigned densities are only relative, and no attempt should be made to assign specific rock types to these densities. However, this density contrast of 0.11 gm/cc within the basement is not geologically unreasonable, since granites (ρ = 2.62 - 2.65 gm/cc) against granodiorites (ρ = 2.68 - 2.74 gm/cc) could produce this contrast.

As can be seen in Figure 15 the solid curve gives an excellent fit to the observed anomaly. The gravity interpretation in terms of these mass anomalies is certainly not unique. For example, the depth to which a possible density variation in the basement extends can only be assumed and presumably other sediment and basement density configurations could be used. Futhermore, the deviation of some of the observed values from the computed smooth curve strongly suggests that density variations, probably associated with faulting, exist within the Tertiary section across the Sand Hills. In any event, it seems clear that we must accept some sort of density variation across the Sand Hills or accept an abnormally low sediment-basement density contrast. For this reason, we believe that a fault is present beneath the Sand Hills, but because of the inherent ambiguities in a gravity interpretation we cannot precisely locate this fault.

The extreme linearity of the southwestern edge of the Sand Hills (Algodones Dunes) has led many people to propose faulting in this region. However, if our interpretation is valid, the main fault break is much nearer the northeastern edge of the Sand Hills than the southwestern edge. A fault in the northeastern part of the Sand Hills is less likely to be a direct prolongation of the Mission Creek-Banning fault than would be a fault on the southwest edge of the dunes.

CONCLUSIONS

The overall trend of the isogal contours is northwesterly, in agreement with the major tectonic grain of the Gulf of California structural province. Thus, additional evidence is given that the Colorado Delta region is indeed a part of the Gulf province.

In the central part of the Imperial Valley, gravity data alone are not too useful for determining sedimentary thicknesses. The gravity field is complicated by vertical and lateral density variations within the Tertiary section and by lateral density variations within the pre-Tertiary basement. On the other hand, the seismic refraction technique was very effective for measuring sedimentary thicknesses in the delta region. Magnetic data would undoubtedly be useful for outlining anomalous basement areas.

The seismicity of the region is useful in defining the overall trend of the San Andreas fault zone. Even with the errors in epicenter location, the greatest seismic activity appears to have been along the San Jacinto fault system.

Continuity of specific major faults in the delta region is difficult to establish using gravity methods alone because of the lack of indicated throw on the faults. Even where well exposed to the northwest, the San Jacinto and Elsinore faults consist of wide zones of branching and interlacing breaks, so that the question is more one of continuity of fault <u>zones</u> rather than continuity of individual single breaks through the delta region. Nevertheless, continuity of the Elsinore fault to the Laguna Salada fault can be established because of the steep gravity gradient zone which can be traced along the west side of the Cucapas to the Elsinore fault to the north.

The Superstition Mountains were elevated along the faults of the San Jacinto zone. The Superstition Mountain fault and the Superstition Hills fault can be traced at least as far south as Heber, California, using the gravity data. For 50 miles southeast from Cerro Prieto, a major throughgoing fault, believed to belong to the San Jacinto zone, is visible on 1935 aerial photographs of the delta region as a fault scarp in the alluvium. Both northwest and southeast of Cerro Prieto a zone of steep gravity gradient is present along the projected strike of the San Jacinto zone from the north, and probably defines the fault zone in this region, although it is not possible to define specific breaks within this zone. Even though continuity of the San Jacinto fault zone through the delta region cannot be firmly established in some areas with gravity data alone it seems fairly certain that continuity of this fault zone can be established by the additional data provided by seismicity (Fig. 3).

No conclusive evidence is presented for establishing the continuity of the Mission Creek-Banning fault southward into the present area of investigation. If our interpretation is valid, a fault is present beneath the Sand Hills (Algodones Dunes), although our limited data indicate that the fault is closer to the east edge of the dunes rather than to the linear west edge of the dunes. It is difficult to extend the Mission Creek-Banning fault to the eastern part of the Sand Hills unless the fault plane curves to the east.

On the west side of the delta region the structural picture is very complicated. A simple explanation that only considers the valley floor faulted down relative to the Peninsular Ranges to the west is not in accord with the known geological facts. The Fish Creek Mountains and the Coyote Mountains were elevated along the Elsinore fault zone and then tilted northward, as pointed out by Dibblee (1954). Within this fault zone the metasediments are upended and have a very steep dip. In the vicinity of the Elsinore fault zone (see Plate 1 and gravity profile A-A') the Bouguer gravity shows a local minimum with gradients approaching 5 mgals/mile. This gravity minimum appears to be related to the known thickness of Tertiary sediments exposed in the Carrizo Valley-Coyote Mountain area, although the gravity field in this region is undoubtedly affected by the large mass deficiency under the Peninsular Ranges. Because of the limited gravity data in the Peninsular Ranges it is not possible accurately to remove the effect of this mass deficiency, so that one at present cannot determine the amount of throw on the Elsinore fault using gravity data.

About eight miles north of Plaster City, opposite Carrizo Creek, the seismic data indicate a basement depth of about 2700 feet. Basement probably deepens slightly towards the upthrust Superstition Mountain fault block and then deepens rapidly eastward from this range. Eight miles east of the Superstition Mountains, seismic data indicate basement depths of at least 11,050 feet. Basement deepens locally to about 12,000 feet in the Seeley area, west of El Centro, and then is prominently exposed southward at Signal Mountain. Southwest of Signal Mountain is Laguna Salada, a graben lowered relative to the Cucapas and the Sierra Juarez. Gravity data suggest a depth of about 19,000 feet to the basement floor in Laguna Salada.

Northeast of Holtville, California, along the east margin of the cultivated region, the depth to basement is about 10,000 feet. The depth to the bedrock floor then probably averages 9,000 - 10,000 feet eastward to the

Coachella Canal. Crossing the Sand Hills basement shallows rapidly to a depth of 2200 feet along the Ogilby-Glamis road and is then exposed eastward at the Cargo Muchacho and Chocolate Mountains.

Twelve miles east of Calexico along the international border the depth to basement is at least 15,400 feet. Thus, it can be stated that the relief between the crest of the Peninsular Ranges to the west and the subsurface bedrock floor approaches 20,000 feet in the central part of the delta region.

West of the Superstition Mountains and east of the Sand Hills, on the margins of the delta region, a layer with a velocity range of 6940 ft/sec - 6970 ft/sec directly overlies the pre-Tertiary basement. The absence of sedimentary velocities greater than this 6940 ft/sec - 6970 ft/sec range probably indicates that a substantial portion of the Tertiary section, present elsewhere in the basin, is absent in these marginal areas.

For the profiles shot in the central part of the delta region, several consistent velocity zones were present overlying the pre-Tertiary basement. A layer with a velocity range of 5650 ft/sec to 6270 ft/sec was present beneath the surface sediments. Beneath the 5650 ft/sec to 6270 ft/sec layer, velocities in the range of 6900 ft/sec to 8770 ft/sec were measured. Except for profiles 5 and 6 along the international border, the pre-Tertiary basement was overlain by a layer with a velocity range of 11,050 ft/sec to 12,500 ft/sec. In the central part of the Imperial Valley, the travel time curves show a gradual increase in velocity with depth up to the 12,000 ft/sec layer rather than distinct sharp breaks in the travel time curves. This abrupt velocity change at the 12,000 ft/sec layer may be related to a regional stratigraphic change that has not been recognized from well data. On profiles 5 and 6, along the Mexican border, a sedimentary velocity of 15,475 ft/sec was detected beneath an 11,930 ft/sec layer. Basement velocities ranged from 18,180 ft/sec to 20,000 ft/sec.

Seismic refraction data indicate a depth of about 21,000 feet to basement near the head of the Gulf of California, opposite San Felipe (Shor, 1961). Our seismic results reveal basement depths ranging from 10,000 feet to 15,000 feet in the Imperial Valley region of the Colorado Delta, with the greatest depths indicated near the international boundary. It would thus be natural to assume that the Gulf structural trough, in general, deepens to the south towards the head of the Gulf of California. However, in the absence of auxiliary data, it is not possible to determine from the gravity data alone whether any basement shallowing does occur between the international boundary and the head of the Gulf of California.

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LIST OF CAPTIONS

Fig. 1. Index map showing general geologic setting.

Fig. 2. Fault map showing primary faults of the delta region.

Fig. 3. Seismicity of the Colorado Delta region.

Fig. 4. Sample seismograms from seismic profile 6.

Fig. 5. Seismic profile 1.

Fig. 6. Seismic profile 2.

Fig. 7. Seismic profile 3.

Fig. 8. Seismic profiles 5 East and 6 West.

Fig. 9. Seismic profile 7.

Fig. 10. Seismic profiles 8 East and 4 West.

Fig. 11. Gravity profile A-A' showing Bouguer gravity from San Diego, California, to Yuma, Arizona, along U.S. Highway 80.

Fig. 12. Gravity profile B-B'

Fig. 13. Gravity profile C-C'

Fig. 14. Gravity profile D-D'

Fig. 15. Gravity profile E-E'

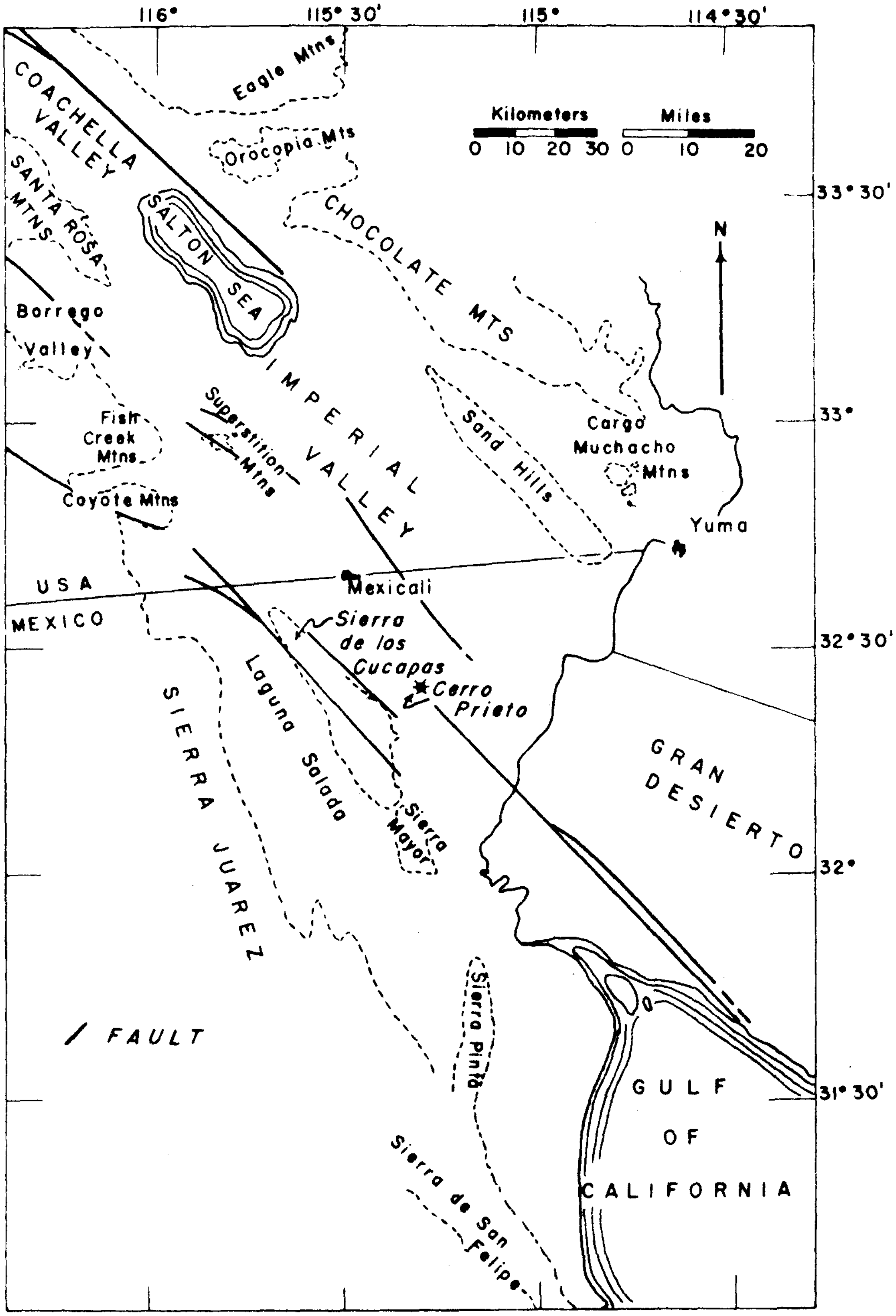
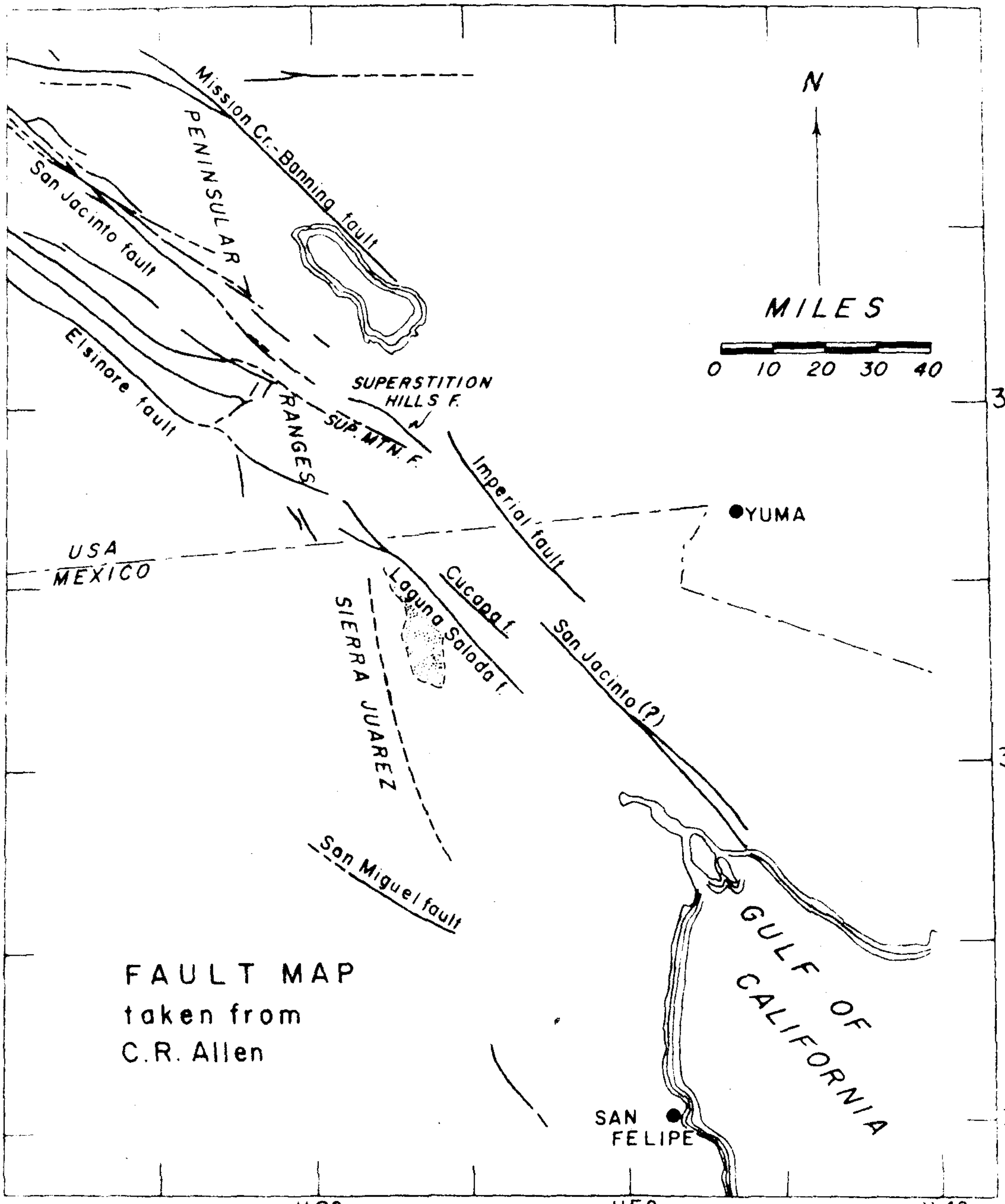

116°
115° 30'
115°
114° 30'
33° 30'
33°
32° 30'
32°
31° 30'
Kilometers
0 10 20 30
Miles
0 10 20
N
COACHELLA VALLEY
Eagle Mtns
Orocopia Mts
SANTA ROSA MTNS
SALTON SEA
CHOCOLATE MTS
Borrego Valley
IMPERIAL VALLEY
Sand Hills
Cargo Muchacho Mtns
Fish Creek Mtns
Superstition Mtns
Coyote Mtns
Yuma
USA
MEXICO
Mexicali
Sierra de los Cucapas
Cerro Prieto
Laguna Salada
SIERRA JUAREZ
Sierra Mayor
GRAN DESIERTO
FAULT
Sierra Pinta
Sierra de San Felipe
GULF OF CALIFORNIA

Fig. 1



FAULT MAP
taken from
C.R. Allen

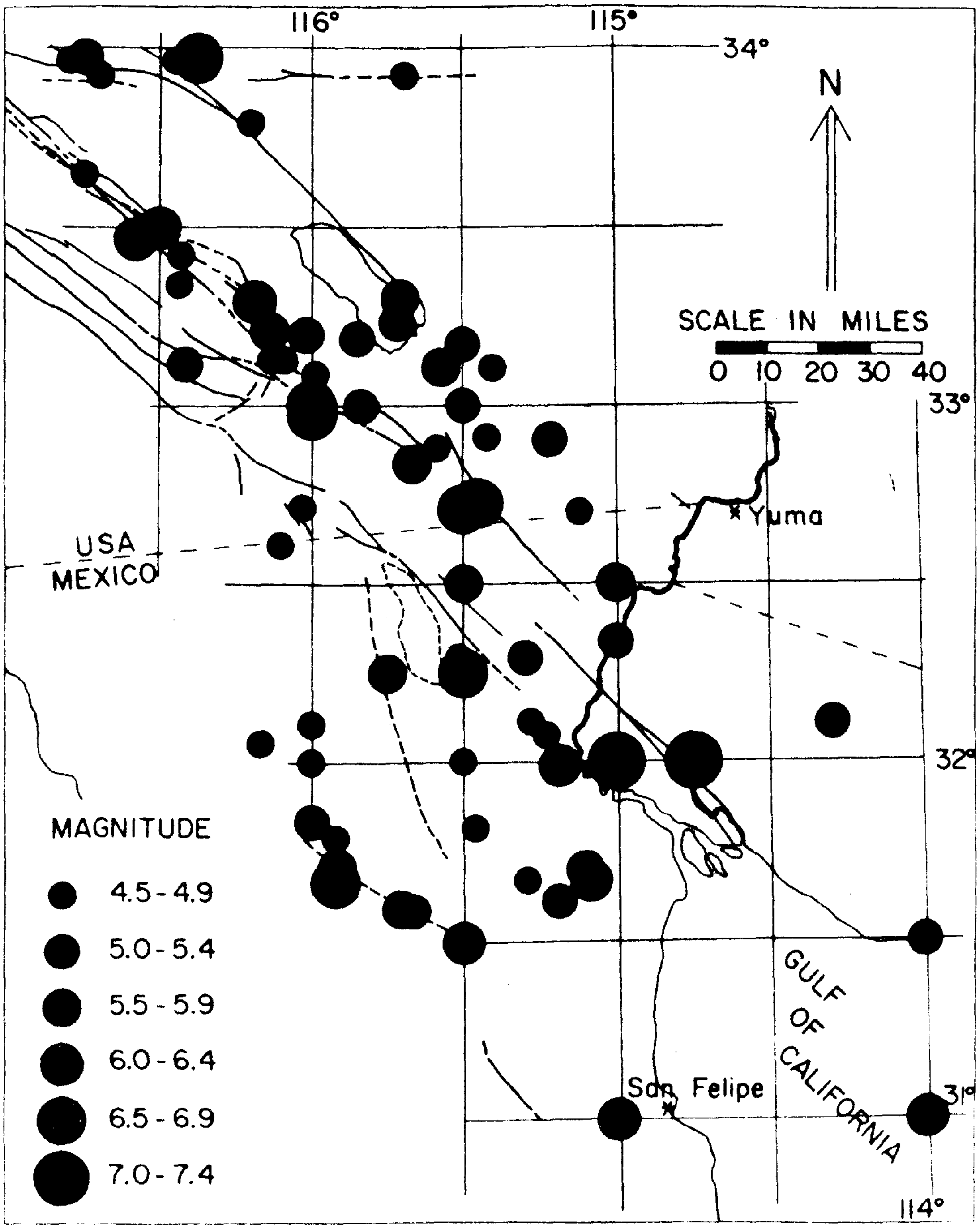

116°
115°
34°
33°
32°
31°
114°
N
SCALE IN MILES
0 10 20 30 40
Yuma
USA
MEXICO
MAGNITUDE
4.5 - 4.9
5.0 - 5.4
5.5 - 5.9
6.0 - 6.4
6.5 - 6.9
7.0 - 7.4
GULF OF CALIFORNIA
San Felipe

Fig. 3

MEXICAN BORDER PROFILE 6

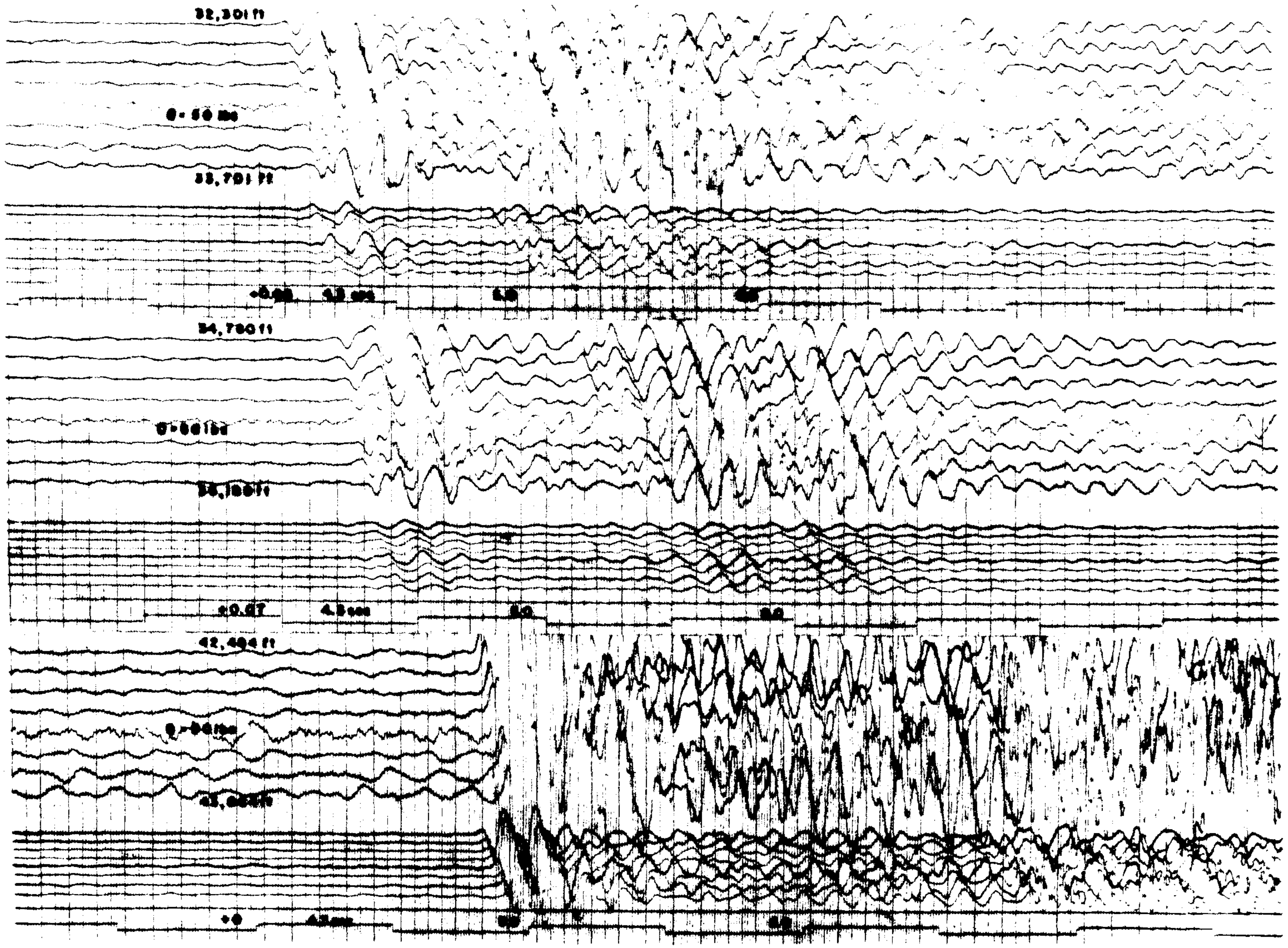


Fig. 4

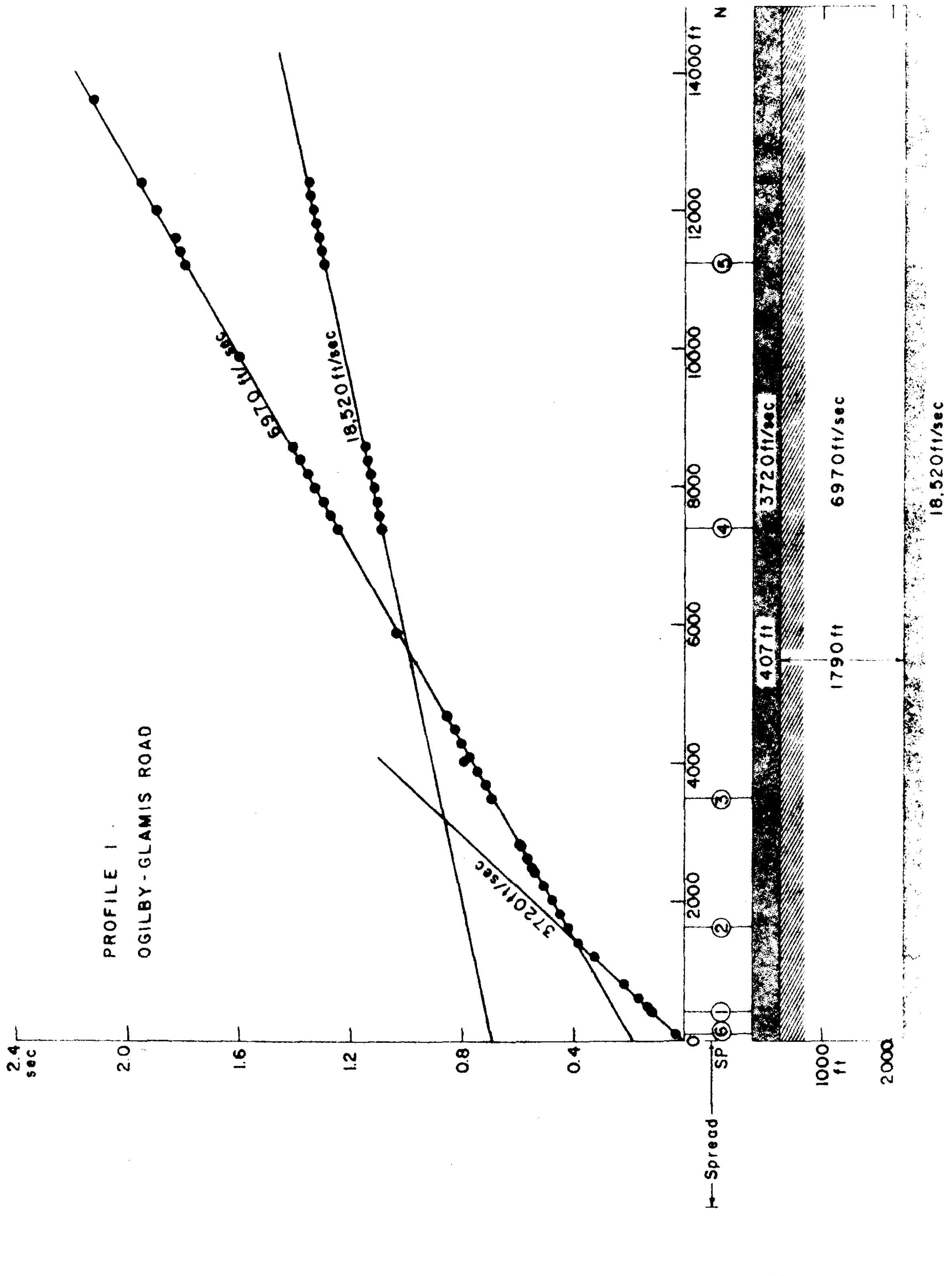

PROFILE I
OGILBY-GLAMIS ROAD
3720 ft/sec
6970 ft/sec
18,520 ft/sec
2.4 sec
2.0
1.6
1.2
0.8
0.4
0
SP
2000
4000
6000
8000
10000
12000
14000 ft
N
①
②
③
④
⑤
⑥
407 ft
3720 ft/sec
1790 ft
6970 ft/sec
18,520 ft/sec
1000 ft
2000
Spread

Fig. 5

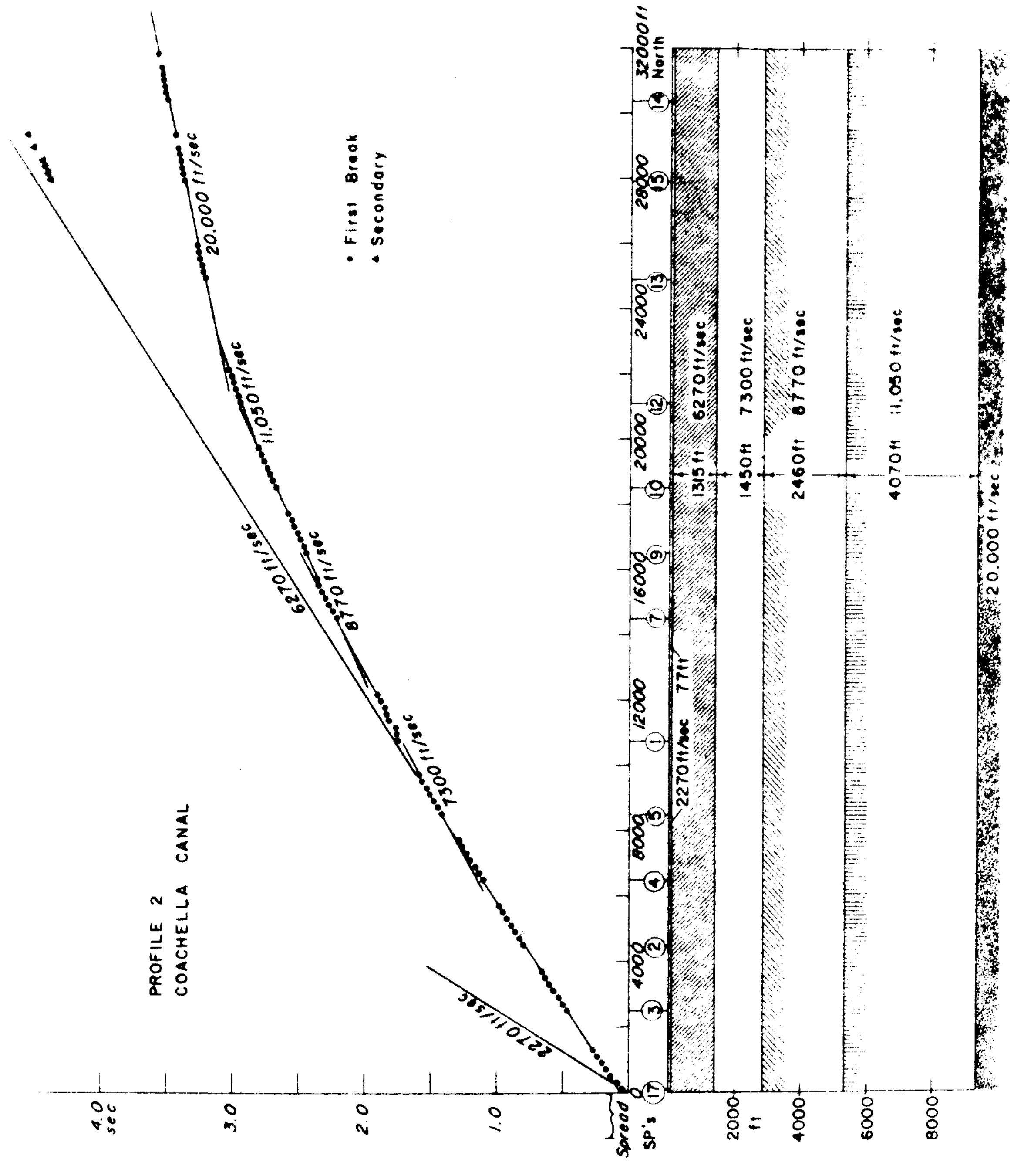

PROFILE 2
COACHELLA CANAL
• First Break
▲ Secondary
4.0 sec
3.0
2.0
1.0
Spread
SP's
2270 ft/sec
7300 ft/sec
8770 ft/sec
6270 ft/sec
11,050 ft/sec
20.000 ft/sec
17
3
2
4
5
1
7
9
10
12
13
15
14
4000
8000
12000
16000
20000
24000
28000
32000 ft
North
2270 ft/sec
77 ft
1315 ft
6270 ft/sec
1450 ft
7300 ft/sec
2460 ft
8770 ft/sec
4070 ft
11,050 ft/sec
20.000 ft/sec
2000 ft
4000
6000
8000

Fig. 6

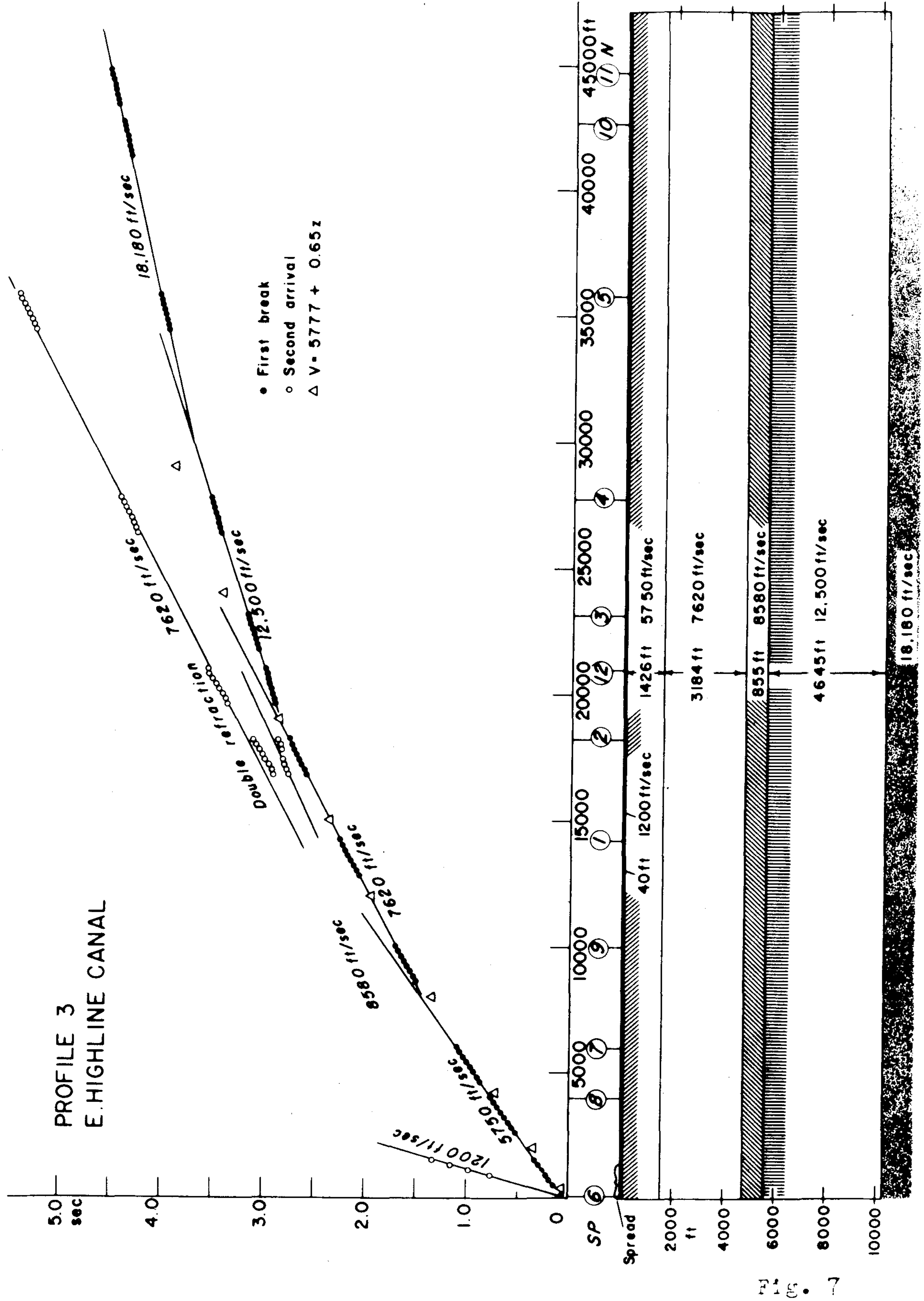

PROFILE 3
E. HIGHLINE CANAL
• First break
○ Second arrival
△ V = 5777 + 0.65z
5.0 sec
4.0
3.0
2.0
1.0
0
SP
Spread
2000 ft
4000
6000
8000
10000
5000
10000
15000
20000
25000
30000
35000
40000
45000 ft
⑥
⑧
⑦
⑨
①
②
⑫
③
④
⑤
⑩
⑪
N
1200 ft/sec
5750 ft/sec
8580 ft/sec
7620 ft/sec
Double refraction
7620 ft/sec
12,500 ft/sec
18,180 ft/sec
40 ft
1200 ft/sec
1426 ft
5750 ft/sec
3184 ft
7620 ft/sec
855 ft
8580 ft/sec
4645 ft
12,500 ft/sec
18,180 ft/sec

Fig. 7

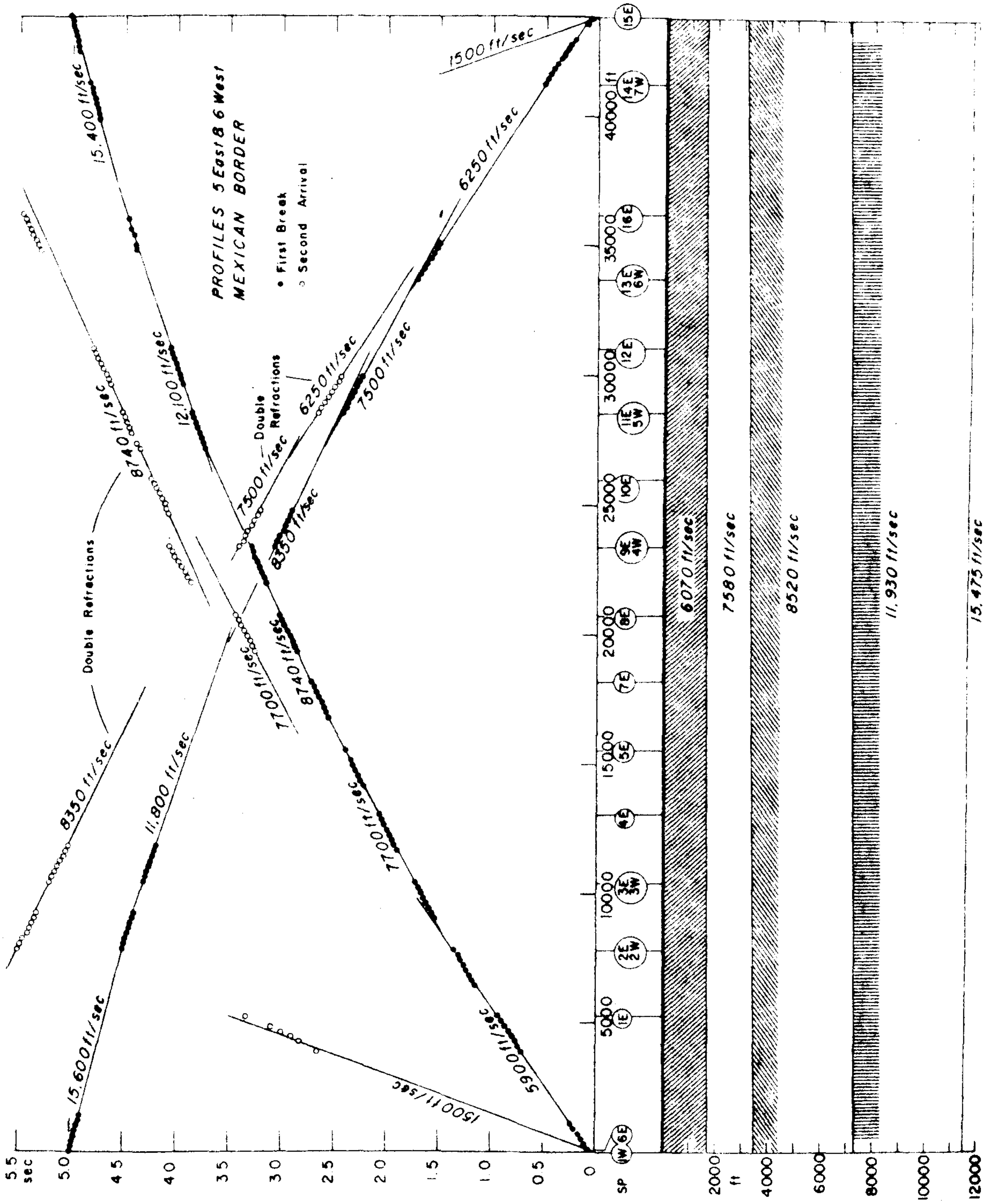

PROFILES 5 East & 6 West
MEXICAN BORDER
• First Break
○ Second Arrival
Double Refractions
Double Refractions
15,600 ft/sec
15,400 ft/sec
8350 ft/sec
11,800 ft/sec
12,100 ft/sec
8740 ft/sec
8740 ft/sec
7700 ft/sec
7700 ft/sec
7500 ft/sec
7500 ft/sec
6250 ft/sec
6250 ft/sec
8350 ft/sec
5900 ft/sec
1500 ft/sec
1500 ft/sec
6070 ft/sec
7580 ft/sec
8520 ft/sec
11,930 ft/sec
15,475 ft/sec
5.5 sec
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
SP
2000 ft
4000
6000
8000
10000
12000
5000
10000
15000
20000
25000
30000
35000
40000 ft
1W 6E
1E
2E 2W
3E 3W
4E
5E
7E
8E
9E 4W
10E
11E 5W
12E
13E 6W
16E
14E 7W
15E

Fig. 8

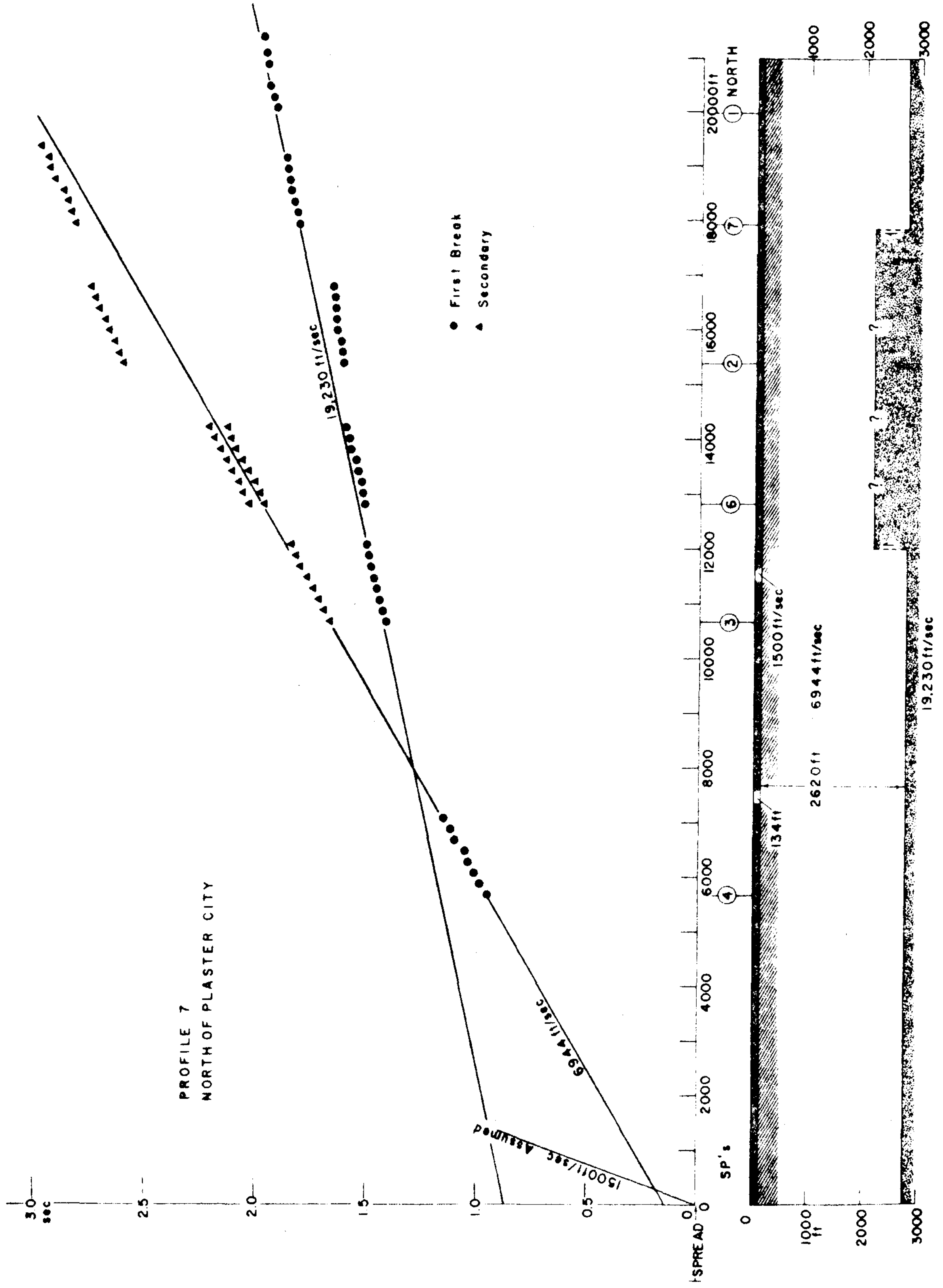

PROFILE 7
NORTH OF PLASTER CITY
● First Break
▲ Secondary
19,230 ft/sec
6944 ft/sec
1500 ft/sec Assumed
3.0 sec
2.5
2.0
1.5
1.0
0.5
0
SPREAD
SP's
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000 ft
NORTH
①
⑦
②
⑥
③
④
134 ft
2620 ft
1500 ft/sec
6944 ft/sec
19,230 ft/sec
?
0
1000 ft
2000
3000

Fig. 9

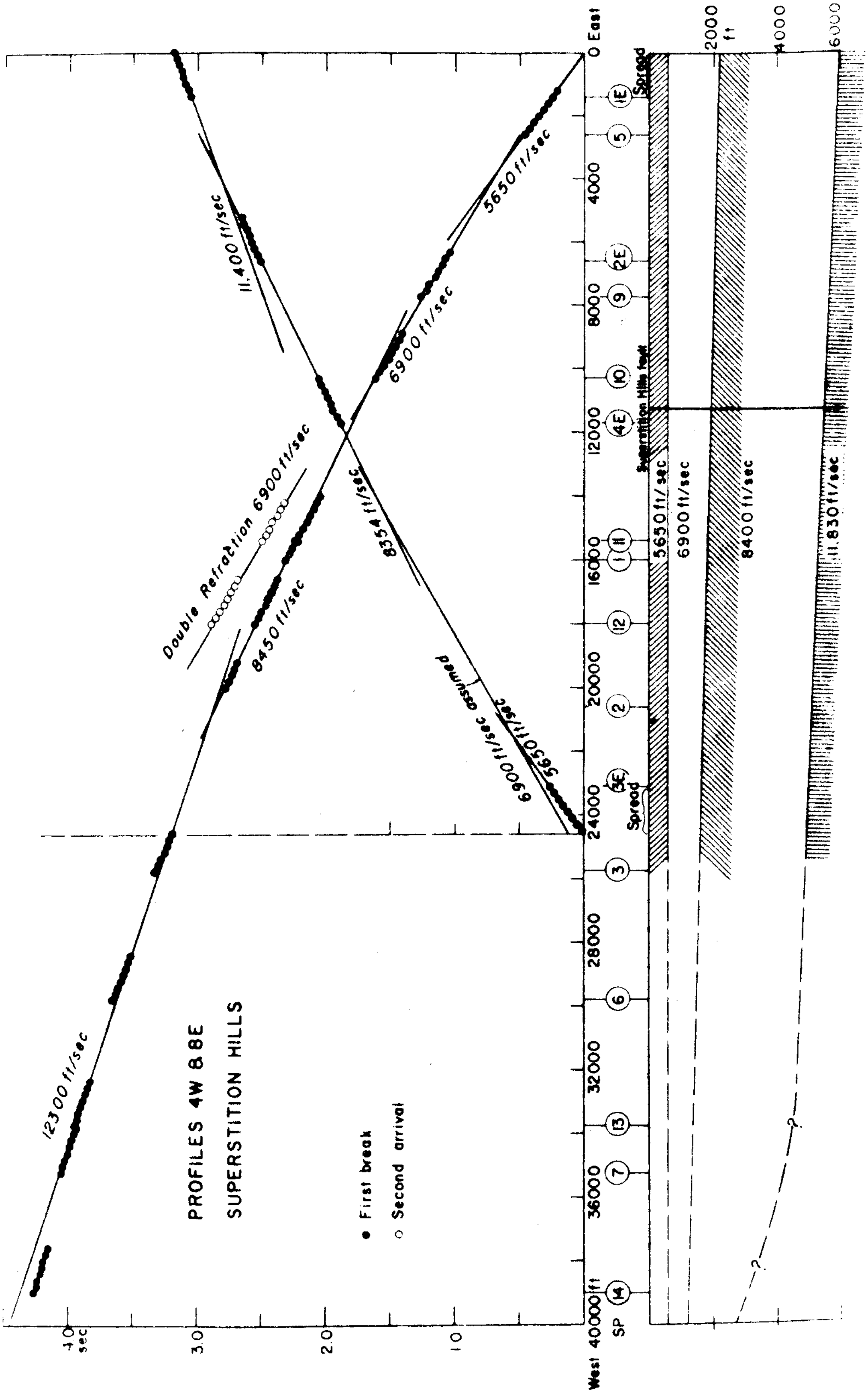

PROFILES 4W & 8E
SUPERSTITION HILLS
● First break
○ Second arrival
12300 ft/sec
8450 ft/sec
Double Refraction 6900 ft/sec
11,400 ft/sec
5650 ft/sec
6900 ft/sec
8354 ft/sec
assumed
6900 ft/sec
5650 ft/sec
4.0 sec
3.0
2.0
1.0
West
East
SP
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
40000 ft
1E
5
2E
9
10
4E
11
1
12
2
3E
3
6
13
7
14
Spread
Spread
Superstition Hills fault
5650 ft/sec
6900 ft/sec
8400 ft/sec
11,830 ft/sec
2000 ft
4000
6000
?
?

Fig. 10

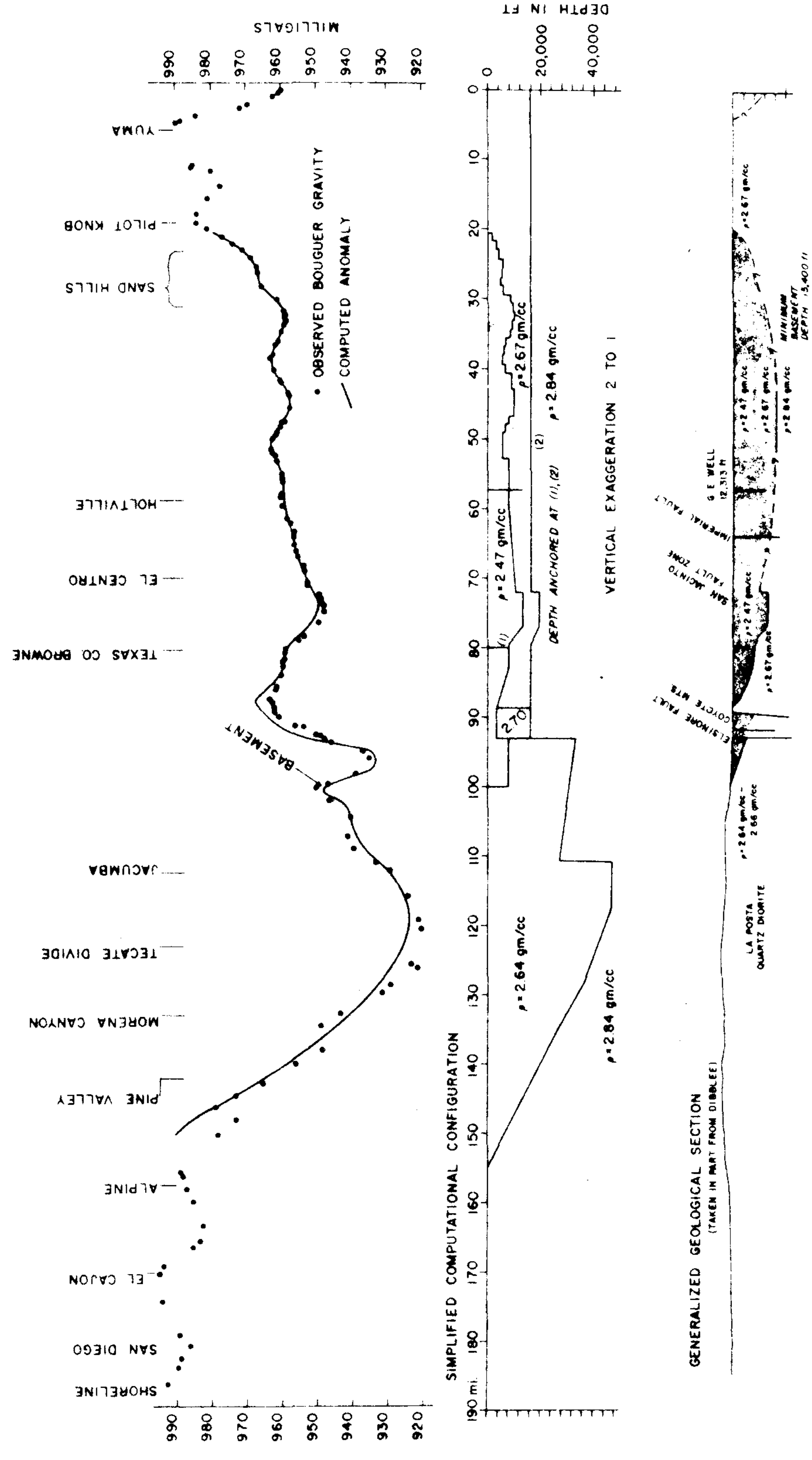

MILLIGALS
990
980
970
960
950
940
930
920
YUMA
PILOT KNOB
SAND HILLS
HOLTVILLE
EL CENTRO
TEXAS CO BROWNE
BASEMENT
JACUMBA
TECATE DIVIDE
MORENA CANYON
PINE VALLEY
ALPINE
EL CAJON
SAN DIEGO
SHORELINE
• OBSERVED BOUGUER GRAVITY
— COMPUTED ANOMALY
DEPTH IN FT
0
20,000
40,000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190 mi.
ρ = 2.67 gm/cc
ρ = 2.84 gm/cc
ρ = 2.47 gm/cc
(1)
(2)
2.70
DEPTH ANCHORED AT (1), (2)
ρ = 2.64 gm/cc
ρ = 2.84 gm/cc
VERTICAL EXAGGERATION 2 TO 1
SIMPLIFIED COMPUTATIONAL CONFIGURATION
ρ = 2.67 gm/cc
MINIMUM BASEMENT DEPTH 13,400 ft
ρ = 2.47 gm/cc
ρ = 2.67 gm/cc
ρ = 2.84 gm/cc
G E WELL 12,313 ft
IMPERIAL FAULT
SAN JACINTO FAULT ZONE
ρ = 2.47 gm/cc
ρ = 2.67 gm/cc
COYOTE MTS
ELSINORE FAULT
ρ = 2.64 gm/cc - 2.66 gm/cc
LA POSTA QUARTZ DIORITE
GENERALIZED GEOLOGICAL SECTION
(TAKEN IN PART FROM DIBBLEE)

Fig. 11

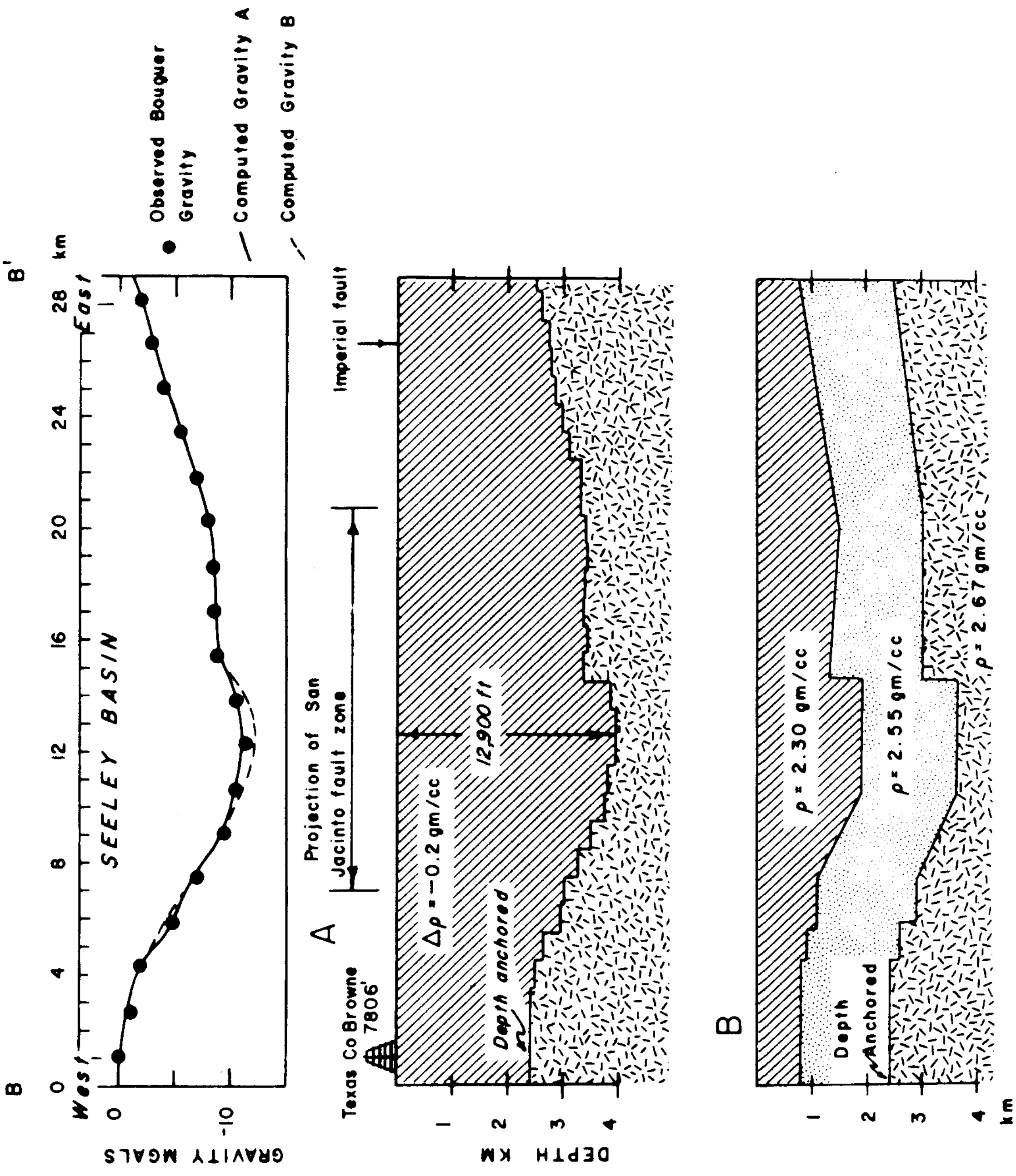

B
B'
West
East
km
0
4
8
12
16
20
24
28
GRAVITY MGALS
0
-10
SEELEY BASIN
Observed Bouguer Gravity
Computed Gravity A
Computed Gravity B
Imperial fault
Projection of San Jacinto fault zone
A
Texas Co Browne 7806'
$\Delta\rho = -0.2$ gm/cc
12,900 ft
Depth anchored
DEPTH KM
1
2
3
4
B
$\rho = 2.30$ gm/cc
$\rho = 2.55$ gm/cc
$\rho = 2.67$ gm/cc
Depth Anchored
km

Fig. 12

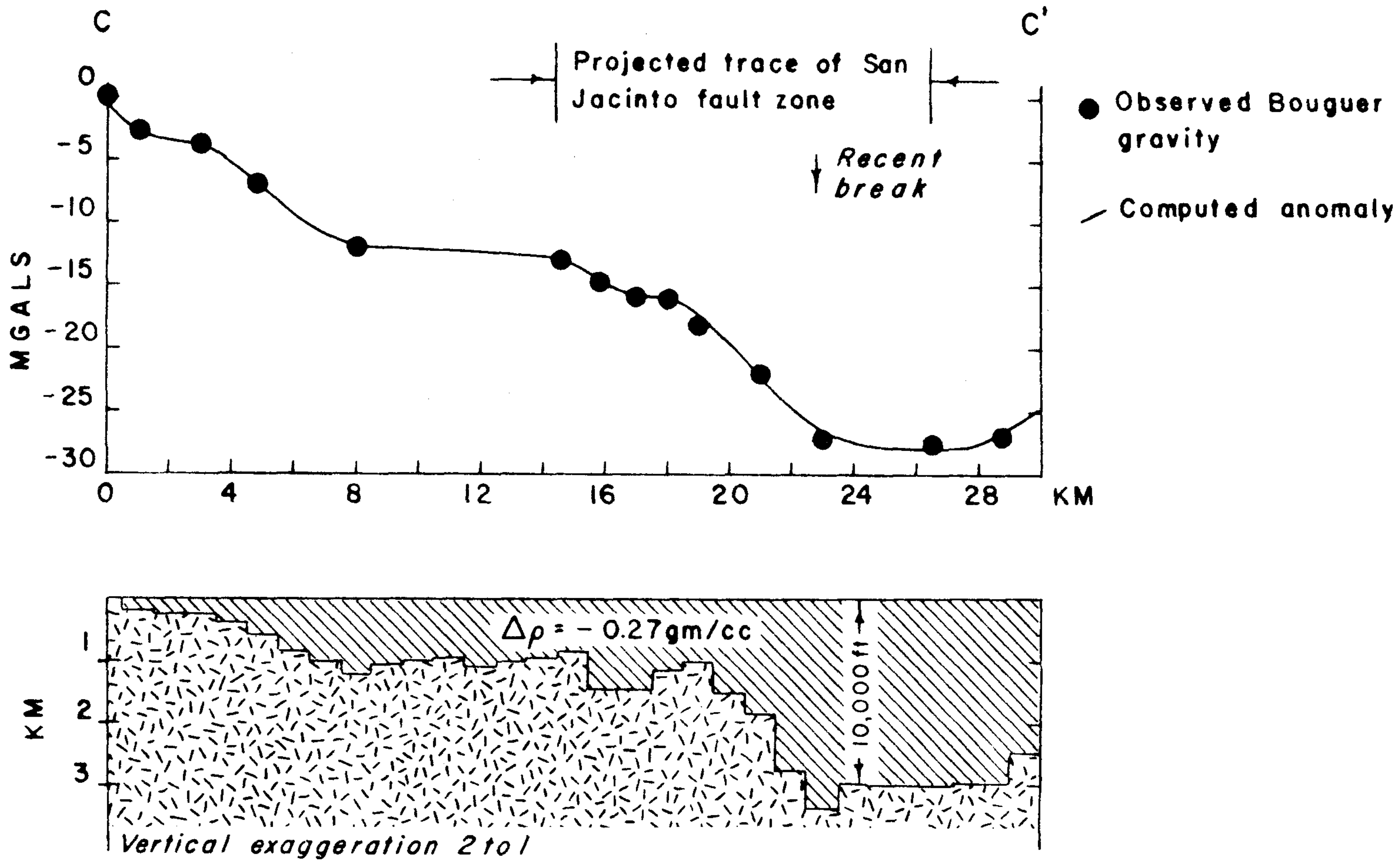

C
C'
Projected trace of San Jacinto fault zone
Recent break
● Observed Bouguer gravity
Computed anomaly
MGALS
0
-5
-10
-15
-20
-25
-30
0
4
8
12
16
20
24
28
KM
$\Delta\rho$ = - 0.27gm/cc
10,000 ft
KM
1
2
3
Vertical exaggeration 2 to 1

FIG. 13

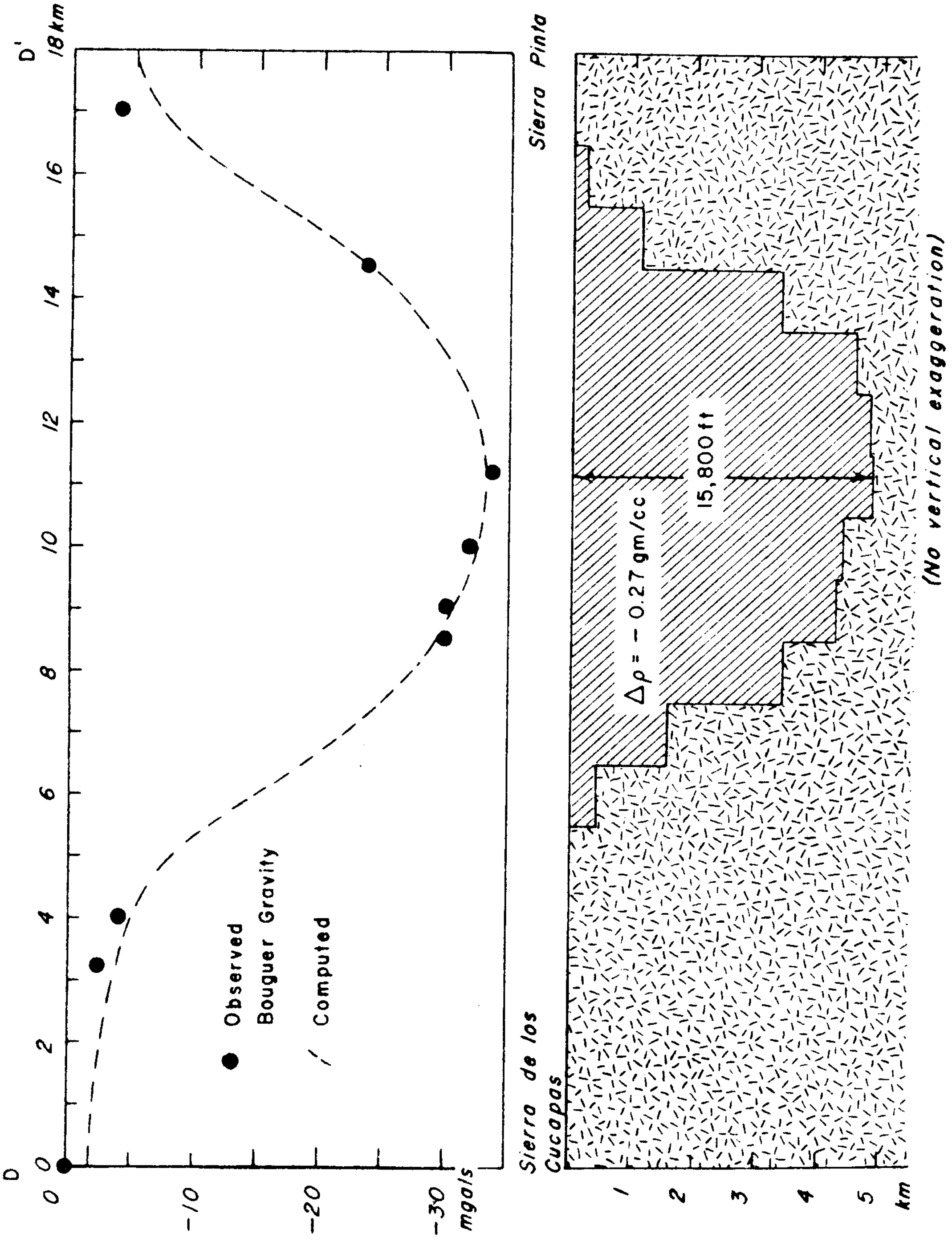

D
D'
0
2
4
6
8
10
12
14
16
18 km
0
-10
-20
-30
mgals
Observed
Bouguer Gravity
Computed
Sierra de los
Cucapas
Sierra Pinta
$\Delta\rho = -0.27$ gm/cc
15,800 ft
1
2
3
4
5
km
(No vertical exaggeration)

Fig. 18

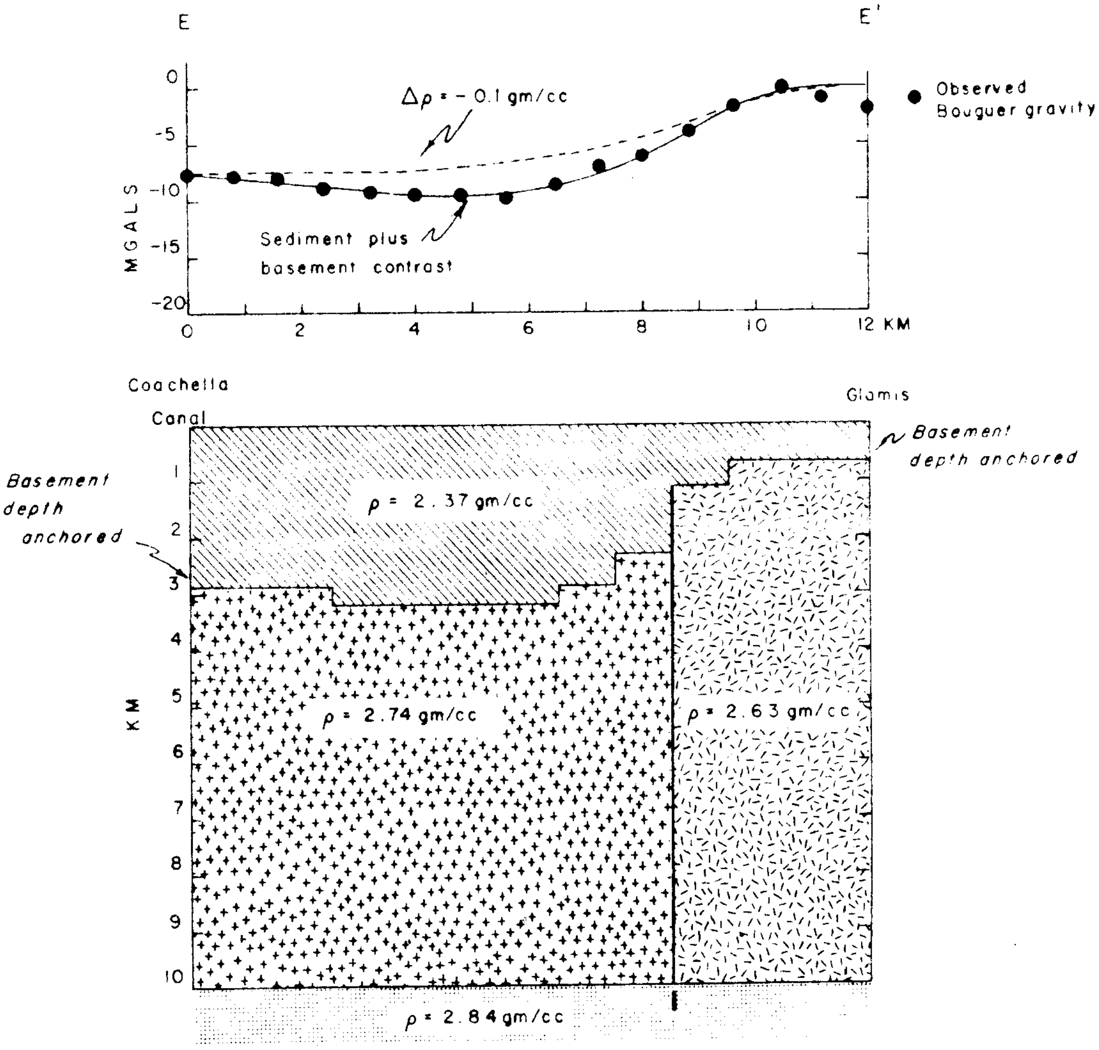

E
E'
0
-5
-10
-15
-20
MGALS
Δρ = - 0.1 gm/cc
Sediment plus
basement contrast
● Observed
Bouguer gravity
0
2
4
6
8
10
12 KM
Coachella
Canal
Glamis
Basement
depth
anchored
Basement
depth anchored
ρ = 2.37 gm/cc
ρ = 2.74 gm/cc
ρ = 2.63 gm/cc
ρ = 2.84 gm/cc
KM
1
2
3
4
5
6
7
8
9
10

Fig. 15

Plate 1. Bouguer Anomaly Map
of the Colorado Delta Region in the
United States.

Plate 2. Bouguer Anomaly Map
of the Colorado Delta Region in Mexico.