

GRAVITY STUDY OF THE  
SOUTHERN CALIFORNIA CONTINENTAL BORDERLAND

by

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Submitted to the Department of Earth and Planetary Science  
on July 24, 1969, in partial fulfillment of the  
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A Bouguer gravity anomaly map of the southern California Continental Borderland is presented. This is separated into regional and residual components. The regional anomaly shows an abrupt change from oceanic to continental structure at the Patton Escarpment, with a gradual thickening of the crust inland and a thinning under the Mojave Desert. The residual anomalies indicate several structural features and show gravity lows over many of the basins, indicating considerable deposition of sediments. Crustal models were calculated along two profiles. These show the presence of antiroots under the larger offshore basins, and a dip of at least 45 degrees at the continental margin which could well be vertical. The general trend of the gravity anomalies in the Borderland is similar to the major structural trends of southern California, with a northwest-southeast trend in the Borderland terminating at the east-west trending Transverse Ranges. The gravity anomalies over the Transverse Ranges are small, and the combination of seismic and gravity data still leads to ambiguous interpretation of the crust under the mountains.

Thesis Supervisor: Shawn Biehler

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## INTRODUCTION

The continental shelf off Southern California is unusual when compared to other ocean margins of the world in that it consists of a broad region of basins and ridges instead of a flat shelf bordered on its outer margin by a steep slope. Shephard and Emery (1941), in the first major study of the area recognized this uniqueness and termed the area the Continental Borderland. The approximate boundaries of this province are shown in Fig. 1.

This study considers only the northern part of this province. (Fig. 2) Its purpose is to use accumulated gravity data combined with the known geology and seismic data to gain some understanding of the submerged and near surface geology, the much broader crustal structure, and the Mohorovicic discontinuity in the Continental Borderland. Presented are a Bouguer anomaly map of the area of Fig. 2, its separation into regional and residual components, and corresponding anomaly maps. Also presented are crustal models along two profiles shown in Fig. 1 calculated from the observed gravity using known seismic depths as control points.

## REGIONAL GEOLOGIC SETTING

## DESCRIPTION OF AREA

The Continental Borderland is one of the best known ocean margins. Bordering the mainland is a narrow strip of relatively shallow shelf from 1 to 15 miles in width; seaward is a broad area of ridges and basins from 35 to 150 miles wide. These terminate at the steep Patton Escarpment which begins at about 2000 feet below sea level and descends to depths of around 12,000 feet within a short horizontal distance. It is believed that this is a fault scarp of considerable extent, and it is roughly comparable in height and steepness with the eastern front of the Sierra Nevada. North of the Santa Barbara channel and south of the area of Fig. 1, the ocean margin loses the distinctive basin-ridge characteristics and assumes the more typical form of a narrow flat shelf with a steep seaward slope. To the east, the Borderland is bounded by the Peninsular Ranges, a north-south trending series of intrusive batholiths. These ranges and the Transverse Ranges to the north separate the Continental Borderland from the topographically and possibly geologically similar Basin and Range province of the western United States.

The area under consideration in this report contains six major basins and several offshore islands (Fig. 2).

There are also at least four basins on land similar to the submarine basins; these are the Ventura, San Fernando, San Gabriel, and Los Angeles basins. The sea basins become gradually shallower, broader and smoother from far offshore to nearshore, generally indicating progressively thicker fills of sediments approaching the land. (Emery, 1960) The trend of the basins and ridges in the borderland is northwest-southeast, until they strike the east-west trending Transverse Range province of which Santa Cruz Island and the Santa Monica Mountains are the major representatives in the area studied. The submarine basins are probably related in form and probable origin to the land basins and both are roughly parallel to the major southern California structural trends. The present sea basins are comparable in many respects to the now filled Los Angeles basin in its earlier stages of development.

The nature of the borderland is not well understood. On the basis of topography, it can be easily compared to the fault block structures of the Basin and Range province. It can also be considered as an area with basins of typical oceanic structure and ridges of continental structure. There are numerous steep escarpments showing considerable relief; for example, the San Clemente Escarpment shows 4500 feet. Such features suggest considerable faulting,

and Emery (1960) published a map of inferred fault patterns based on the topography.

#### GEOLOGY

The known geology of the offshore area is summarized by Emery (1960). Detailed geology of the nearby land areas and of the offshore islands is available on the California Division of Mines and Geology geologic maps of California, Santa Maria, Los Angeles, Long Beach, Santa Ana, and San Diego sheets; and in Woodford et al (1954), Jahns (1954), Bailey and Jahns (1954) and Emery (1954). Only a brief summary is given here.

Rocks of Miocene age have by far the widest distribution and have been reported from all the islands and most of the available sea floor samples. Miocene extrusive volcanics, mostly andesite and basalt, are common on the islands and on some of the banks with andesite concentrated on the landward half of the borderland and basalt in the seaward half. In particular, they are found on Santa Barbara and San Clemente Islands and on Cortes and Tanner Banks.

Metamorphics are found in place in several areas. Those on Santa Catalina, Thirtymile Bank, and the Palos Verdes Peninsula are part of a distinctive Jurassic-Cretaceous Franciscan complex. There is no continuation



between this complex and the metamorphics found in the Transverse Ranges, Santa Cruz Islands, and on the eastern side of the Newport-Inglewood fault.

The sea basins all have considerable accumulations of sediments ranging in age from Miocene at depth to the relatively unconsolidated mudstones and sandstones of Pliocene to Recent. The land basins are essentially filled with Miocene and post-Miocene sedimentary fill, causing considerable downwarping of the basement. Depth of this fill is approximately 30,000 feet in the Los Angeles basin (McCulloh, 1960) and about sixty percent of it is post-Miocene (Emery, 1960). The most common Miocene sediments are shales and cherts with some limestones; the post-Miocene sediments are dominantly mudstones and sandstones.

The Santa Ana Mountains are the northern extension of the Peninsular Range batholith, and are plutonic intrusives, mostly tonolites, granodiorites, and gabbroic rocks.

## GEOPHYSICAL STUDY

## PREVIOUS WORK

The only major seismic study of the Continental Borderland is that by Shor and Raitt (1956). Their work includes one major cross section showing crustal structure and several shallow structure sections. Major seismic crustal studies on land include a study from Santa Monica Bay to Lake Mead by Roller and Healy (1963), and a crustal study from San Francisco to Los Angeles along the California coast by Healy (1963).

A gravity study of the Continental Borderland was done by Harrison, von Huene, and Corbato (1966) and generally includes the area under consideration in this paper. They had fewer stations however, and this paper is essentially a continuation and reevaluation of their work. Von Huene and Ridlon (1966) studied the gravity in the Santa Barbara Channel and presented Bouguer and free air anomaly maps. A detailed Bouguer anomaly map of the northwestern part of the Los Angeles basin, and a study of gravity and geology of the basin were published by McCulloh (1957,1960). Studies of the adjoining areas include a detailed gravity study of the Coachella and Imperial valleys by Biehler (1964) and Biehler, Kovach and Allen (1964). Mabey (1960) studied the gravity anomalies in the western Mojave desert

on the northern side of the Transverse Ranges. These studies of adjoining areas were used to obtain data for the crustal models presented in a later section of the paper.

#### SOURCES AND REDUCTION

The gravity data used in this study was compiled by S. Biehler from published sources, many unpublished ones, and from his own personal observations. The reduction of the data was carried out with the use of his computer programs. These reduced the free air anomalies to Bouguer anomalies using a Bouguer density of 2.67 gm/cc on land, and filling the water areas with fill of density 2.67 gm/cc. A program which fits a surface to the observed gravity data by the method of least squares was used to compute a regular grid of gravity values from random observations. This grid was then digitally contoured at 10 milligals to produce a Bouguer gravity anomaly map (Fig. 3). These grid point gravity values are averaged around a 20 kilometer radius to produce the regional gravity value at a point; subtraction of the regional from the Bouguer gravity value yields the residual gravity at that point. These values are also digitally contoured at 10 milligals, producing regional and residual gravity anomaly maps (Figs. 4 and 5). These maps are 20 kilometers

smaller than the Bouguer map as a result of the averaging process. The machine contoured Bouguer anomaly map was compared to a hand contoured map of the same data with a contour interval of 5 milligals. There was excellent agreement between the two methods with the machine contoured values tending to be somewhat smoother. For further discussion of the computer processing of gravity data, see Biehler (1964).

No terrain correction was applied to the ocean values. It would lead to serious errors only in regions of very steep gradient. Accuracy is conservatively estimated at 5 to 10 milligals in areas with adequate coverage, and 10 milligals in areas where coverage was sparse.

#### GRAVITY INTERPRETATION

##### BOUGUER ANOMALY MAP

The Bouguer anomaly map is shown in Fig. 3. The basic features revealed are similar to those shown by Harrison et al (1966) with perhaps somewhat more detail obvious in the southwest corner. The general trend of the anomalies is northwest-southeast over the Continental Borderland; it changes rather markedly to an east-west trend over the Transverse Ranges. The values range from a high of 134 milligals in the southwest corner to -130 milligals in the northeast corner. It is evident that

there is a prominent northwest-southeast trending regional gradient present. Superposed on this are many lows and highs, often associated with basins and topographical highs. The Bouguer anomaly shows a strong correlation with topography, implying that the entire area is generally in isostatic equilibrium. One of the striking features of the map is the strong gradient associated with the Transverse Ranges where a rise of over a hundred milligals is seen between the coast and Santa Cruz Island. Prominent lows are associated with the Santa Monica, Los Angeles, and southern end of the Santa Barbara Basins. Prominent gravity highs are associated with the Santa Monica Mountains and the Channel Islands, and the San Joaquin Hills near Laguna Beach. There is no distinct gravity anomaly associated with the high mountains of the San Gabriel and San Bernardino ranges. The offshore areas are characterized by broad highs and lows. The large blank area west of the coast near San Diego was not contoured due to a lack of data. Similarly, the edges of the map, particularly the western and southern edges were contoured on sparse data and may not be accurate.

#### REGIONAL ANOMALY MAP

The regional map (Fig. 4) can be a valuable indicator

of the deep crustal structure and Moho depth. The effect of most near surface features of extent less than 20 kilometers is removed by the averaging process, and the regional anomaly represents the effects of features at depths greater than 7-10 kilometers. For near surface features which are particularly large, some residual effect will still remain in the regional anomaly; this would most likely be true for the wide basins such as the San Nicolas and Santa Monica basins. The residual effect not removed is probably small however, and is not a significant factor in the regional map.

The regional anomaly map shows a strong northwest-southeast gradient over the land and near shore areas which broadens and loses much of its characteristic trend over the Borderland. The gravity values range from 70 milligals in the southwest corner to -100 milligals in the northeast corner. There is a strong gradient present leading onshore from Santa Cruz Island, indicating a rapid thickening of the crust. This strong gradient begins to die out south of the Transverse Ranges, although the general trend is still present. There are areas of rather constant gravity anomaly over considerable areas corresponding to the San Nicolas Basin, the Santa Cruz Basin, and the Santa Catalina Basin. There is also a

weak indication of such an effect under the Santa Monica and Los Angeles Basins. There is no major change corresponding to the Transverse Ranges indicating no associated deep crustal feature. The regional map indicates, in general, a fairly constant crust-mantle interface under the southwest portion of the area studied, which thickens rather rapidly approaching the coast and under the land surface.

The rather prominent high of about 20 milligals associated with the San Nicolas Basin is interesting because normally basins have thick sediment deposits and exhibit a negative anomaly. The positive anomaly over the San Nicolas Basin is certainly not due to basement uplift as can be seen in Shor and Raitt's seismic data (1956), nor is it due to compaction effects. The best remaining possibilities are a crustal thinning or a density change in the mantle under the basin. The possibility of a density change corresponding to the basin is unlikely. Although there is possibly a gradational density change from oceanic to continental mantle, this does not seem to be localized in any area. This would imply a thinning of the crust under the basin, and may be the result of a major discontinuity in the Moho. Such an effect would also be reasonable to satisfy isostasy. A more complete

discussion of this type of structure and other examples are found in Biehler (1964). The two crustal models in a later section both indicate such thinning under the basins of the Continental Borderland.

#### RESIDUAL ANOMALY MAP

The residual map (Fig. 5) shows a pattern of high and low gravity values. These residual anomalies are generally due to near surface features such as changes in basement rock types and basement-sediment contacts, and in many areas are closely related to structural relief of the basement. It should be noted, however, that they do not always correlate with major topographical features and sometimes trend between them as, for example, the high between the lowest part of the San Nicolas Basin and San Clemente Island. This implies that the residual anomalies may also reflect deeper basement density contrasts as well.

The high over the San Joaquin Hills near Laguna Beach was interpreted by Mc Culloh (1960) as a gabbroic igneous intrusion into the basement rocks. There is no surface outcrop of such rocks, but such an intrusion would be similar to structures found in the Peninsular Ranges to the southeast. The high over the Palos Verdes Peninsula



is bounded on the east by the Newport-Inglewood fault. As mentioned earlier, the basement under the peninsula is composed of Franciscan metamorphics bounded by the fault. This would indicate that this high gravity anomaly is associated with the Franciscan basement rocks. Although this high does not appear to continue under the Santa Monica Bay, it is known that the associated basement is fairly constant at a depth of 2-3 kilometers under the coast. (McCulloh, 1960). Also, there is some evidence that the Newport-Inglewood fault continues to the Santa Monica Mountains chiefly on the basis of the alignment of oil deposits in the sediments of the Los Angeles basin. (Woodford et al, 1954) The apparent change in the residual values is possibly due to a dipping of the basement layer under Santa Monica Bay. To the west, the Palos Verdes high is bounded by the San Pedro escarpment, and correlated with it both to the north and south until the escarpment is no longer a recognizable feature. To the south, it continues over the rather flat area offshore and coincides with the closure of the south end of the San Pedro Basin. The extent of this high, which is apparently bounded on both sides by fault zones raises the possibility that it is one continuous fault block. There is also a possibility that it represents a plunging

anticlinal uplift. Emery (1960) shows a hypothetical cross section across the San Pedro Shelf based chiefly on rock samples of the bottom which shows such a structure. The apparent continuity of the gravity feature across the Santa Monica Bay and the available rock samples from the bay would also support such a hypothesis. (Emery, 1960)

The high over Santa Catalina Island is also associated with a basement complex of Franciscan metamorphics. It can be traced to the north along the Catalina Ridge and over the small rise separating the Santa Monica and San Pedro Basins. This high is bounded on the west by the Catalina Escarpment. The apparent closure at the north end of the San Pedro Basin raises the possibility that the Santa Catalina Block is essentially continuous with the Palos Verdes block, and the San Pedro Basin represents a graben in the basement rocks.

There is a distinctive high associated with Thirty-mile Bank continuing around the north end of the San Diego trough. The western edge corresponds roughly to the steep slope west of Thirtymile Bank. There is an area of high anomaly under the small rise west of San Clemente Island extending across the southern end of the Santa Catalina Basin. It apparently abuts against the San Clemente

Escarpment to the west, and forms an extension of the Catalina Escarpment on the east.

One of the most striking areas of high gravity is that trending midway between the San Clemente Island and the deepest part of the San Nicolas Basin. Another similar high is found along the eastern edge of the Santa Cruz Basin extending under San Nicolas Island to the south and joining the east-west trending high associated with the Channel Islands and the Santa Monica Mountains. In general, except for a relative low under Santa Barbara Island and the land surrounding it, these form one continuous area of high gravity anomaly extending from slightly west of San Clemente Island to the Transverse Ranges, and possibly defines a distinct structural block.

The high values north of the Los Angeles basin are associated with the basement outcropping in the Santa Monica Mountains and possible basement uplift on the east side of the San Fernando Valley. There are also minor areas of high gravity anomaly identified with the Tanner Basin and the western part of the Santa Rosa-Cortes Ridge.

The most striking areas of low gravity anomaly are associated with the Santa Monica and Los Angeles Basins. The Santa Monica Basin is probably comparable to the Los

Angeles basin in total depth of sediments and may be deeper. This cannot be determined from the gravity, however, as the more negative anomaly is not necessarily an indication of greater depth of sediments, particularly when dealing with depths of 30,000 as is found in the Los Angeles basin. (McCulloh, 1960) This negative anomaly is, in fact, an interesting feature. The maximum anomaly arising from a deep sedimentary basin is generally less than -50 milligals, which is close to that observed in the Santa Monica basin. Compaction effects effectively prevent more negative anomalies. (Biehler, 1964) If there is an antiroot under the basin as may be weakly indicated in the regional anomaly, a correction for its effect would lead to an even more negative anomaly. It is possible that there is no antiroot and that the area has not yet reached isostatic equilibrium with the sediments deposited. Or, if an antiroot is present, it would be necessary to have a layer of sediments of unusually low density to offset the effects of the mass increase at the Moho.

In general, the remaining areas of low anomaly correspond roughly to basins and recent igneous intrusives.

It is interesting to consider possible alignment of some of the Borderland features on the basis of

gravity. Fig. 6 is an outline of the areas of high and low residual anomalies on the topographical map of the area studied. Several possible relationships appear. Already considered is the large block associated with basement of Franciscan metamorphics and bounded by possible faults on both sides. There is an apparent continuity of Santa Monica basin, Catalina basin, and San Clemente basin with respect to residual lows. A similar alignment of gravity lows includes the Los Angeles basin and the coastal and offshore regions extending to San Diego; the San Joaquin Hills high can perhaps be discounted as being rather recent intrusives into the existing structures. Also already considered was the long block showing high anomalies in the Santa Cruz and San Nicolas basins.

Thirtymile Bank resembles Catalina Island in structural form, and basement rock has been dredged from it. It is possible that the steeply sloping eastern side of Thirtymile Bank has a counterpart in the Catalina Escarpment and that they are related by faulting.

San Clemente is composed dominately of hard extrusives as is Fortymile Bank and Santa Barbara Island. The residual low around San Clemente Island and Santa Barbara Island is probably not related to the surface volcanics. Harrison et al (1966) indicate that mid-Tertiary andesites and

basalts range in density from 2.50 to 2.70 gm/cc. Assuming that similar densities hold for the Miocene volcanics on the islands mentioned, the effect on the gravity anomaly would be almost removed by the 2.67 gm/cc fill used in the reduction of the gravity data. Thus, the low residual anomalies possibly represent deeper features of lighter intrusive material. Harrison et al (1966) deduced a belt of deep seated intrusives near San Clemente and Santa Barbara Islands from magnetic anomalies, which corresponds roughly to the areas of low anomaly shown. It is possible that the two islands are part of a single block of recent volcanic material resulting from this intrusive belt.

There is also a strong resemblance between San Clemente Island and Fortymile Bank. They are both mostly recent igneous extrusives; the San Clemente Escarpment appears to have a counterpart to the west of Fortymile bank, the lengths of the two are similar. Shephard and Emery (1941) originally attempted to explain a possible fault relation between the two features; the apparent correspondence of the gravity data lends strength to this possibility.

When we consider both of the relationships just discussed, it appears possible that the large block of

material outlined by the San Clemente-Fortymile Bank Escarpments and the Santa Catalina-Thirtymile Bank Escarpment is one large fault block. The area of high gravity anomaly immediately to the east of San Clemente would correspond roughly to the highs north of Catalina Island, and the high and low over Thirtymile and Fortymile Banks respectively would line up roughly with Catalina and San Clemente Islands.

The Santa Rosa-Cortes Ridge and Tanner Bank form a continuous area of low gravity values, and are possibly recent volcanics or deep volcanic intrusives similar to that postulated for San Clemente and Santa Barbara Islands; however, only Miocene and Eocene marine sediments have been dredged from these two areas, and support for the idea is small.

It should be noted that all of the Borderland gravity features are terminated at the Transverse Ranges. There are areas of low anomaly associated with the Ventura Basin and the San Fernando Valley; however, these basins do not seem to be part of the Borderland, but reflect the trends of the Transverse Ranges. There is some possibility that the San Fernando Valley represents an en echelon offshoot from the southeast part of the Ventura Basin. Similarly, there is a low associated with the Santa Barbara

Basin as can be seen from the Bouguer map; again, the general trend of this basin is not that of the Borderland basins, but reflects the Transverse Ranges.

In general, the residual gravity reveals several possible tectonic blocks, and emphasizes the already existing knowledge of the structural trends of the Borderland and Transverse Range provinces. There is no significant disagreement with the results of Harrison et al (1966), although the residual gravity features have been discussed in somewhat more detail.



## CRUSTAL MODELS

Crustal models were constructed along two profiles (Fig. 1). The observed Bouguer and regional gravity and the topography for Profile 1 are shown in Fig. 7; also noted are the major features which it crosses. This profile is very similar to those constructed by Harrison et al (1966) for a gravity study and by Shor and Raitt (1956) from seismic refraction studies. Gravity values for the western extension across the Patton Escarpment are taken from a survey line of Harrison's extending over the San Juan Seamount (Fig. 1, Profile 3). These values are projected onto the line of Profile 1 and a reasonable regional gradient is fitted to the Bouguer anomalies. Gravity values for the eastern extension past the edge of the map are taken from Biehler et al (1964). Harrison et al (1966) fitted the Bouguer gravity anomaly; this paper, however, considers only the regional gradient and assumes that any changes arise in the Mohorovicic discontinuity, or Moho.

Profile 2 is the westward extension of the crustal section constructed by Roller and Healy (1963) from Lake Mead to Santa Monica Bay. The observed Bouguer and regional gravity, topography, and major features crossed are shown

in Fig. 9. Again, the gravity values over the Patton Escarpment are taken from Profile 3 and projected onto Profile 2. Gravity values for the San Gabriel Mountains and the Mojave Desert were taken from unpublished data of S. Biehler (personal communication).

The two dimensional crustal models fitted to the gravity observations are based wherever possible on seismic refraction studies. The assumption of two-dimensionality is quite good over the elongate ridges and basins in the area considered; over a small island, it leads to an underestimate of the crustal thickness. A two layer crust is assumed and an approximation is made to the upper layers using seismic data of the near surface structure. There is, of course, some question as to how real the resulting Moho will be. Since only the regional anomaly was fitted, the upper layers should have only a small effect on the calculated model. The averaging process used to obtain the regional anomaly effectively removes the effects of small scale features of the order of 20 kilometers. However, regional anomalies resulting from systematic changes in near surface density over large areas cannot be distinguished or removed. It is assumed that such effects are small over the area studied.

Velocities for the upper layers below the sedimentary

layer range around 6.2 km/sec, in the second layer around 7.0 km/sec, and in the mantle around 8.2 km/sec under the ocean and 7.8 km/sec under the mainland. Densities are derived from these seismic velocities and from the density-velocity curves of Woolard (1962). The upper layer was considered to be 2.67 gm/cc, the second layer 2.95 gm/cc, and the lower layer 3.30-3.40 gm/cc. For determining variations of crustal thickness, it is necessary, in addition to assuming densities, to fix the crustal thickness in at least one point. There were several seismic determinations available for each model, but it proved impossible to fit all of them. In general, an attempt was made to fit as closely as possible the Moho determination of 24 km along the Catalina Ridge reported by Shor and Raitt (1956), and the remainder of the model was juggled to fit this. The computed gravity is obtained by the method of Talwani, Worzel, and Landisman (1959). At the end of each model, an infinite slab of the thickness of each layer at the ends of the model is assumed.

#### PROFILE 1

The regional anomaly of Profile 1 (Fig. 7) is about 230 mgal over the oceanic deeps and drops steeply to about 60 mgal as it crosses the continental shelf. There is a

pronounced rise of about 20 mgal under the San Nicolas Basin, then a fairly uniform drop to -90 mgal under the San Jacinto Mountains, rising to -60 mgal under the Mojave Desert. Superposed on this regional gradient are several large second order anomalies shown in the Bouguer values and representing near surface features. The most striking of these is the sharp dip in the Bouguer anomaly west of the continental margin. This is related to the position of the western extension which crossed the San Juan Seamount, a small, somewhat conical structure rising 10,000 feet from the ocean floor. It is believed to be a volcanic feature. The associated Bouguer anomaly is not a real feature, as the Bouguer correction assumes infinite extent and this feature is definitely not. The terrain correction is vital on a feature such as this. The associated Bouguer anomaly is ignored in drawing the regional anomaly, and the dip is not shown in the Bouguer anomaly of Profile 2.

A very real feature is the steep drop in the Bouguer anomaly as it crosses the continental shelf. The gradient of the Bouguer anomaly at the continental margin is too steep to be explained by changes in crustal thickness or in mantle composition alone. Even a vertical Moho gives an anomaly very close to the regional anomaly shown.

Thompson and Talwani (1964), in a crustal study in northern California, infer a thick sedimentary body on the continental slope to account for this, and this is probably a reasonable explanation for this area as well. There are four highs of about 20 mgal. Three of these are associated with the highs discussed earlier under Tanner Basin, western San Nicolas Basin, and the south end of the San Pedro Basin. The fourth seems to be associated with the Peninsular Range batholith and perhaps is the result of a basic intrusion in the basement. There are lows corresponding to the San Nicolas basin and the Catalina basin, as would be expected for areas of sedimentary deposition.

Seismic data for this profile comes from Shor and Raitt (1956), and their crustal model was used as a starting point for the computations in this paper.

Several models were computed for Profile 1; two are shown in Fig. 8. Model 1 assumes a density of 3.30 gm/cc for the mantle layer. Model 2 assumes a density of 3.30 gm/cc east of the San Andreas fault under the Mojave desert and a density of 3.35 gm/cc under the ocean. This model is based on the velocity difference of about 0.4 km/sec between oceanic and Basin and Range type mantles (Pakiser, 1963).

Model 1 shows the Moho at a depth of 11.5 km west of the continental shelf dropping to a depth of 21 km as it crosses the Patton Escarpment. As shown, the slope of the discontinuity is about 45 degrees. Calculations were made assuming a vertical slope and still fitted the assumed regional well. A more accurate determination of the slope cannot be made without further gravity measurements and greater consideration of the upper layers. The Moho slopes fairly evenly to 26 km under the Tanner Bank, then rises 7 km under the San Nicolas Basin, showing the antiroot structure discussed earlier. It drops back to 22.5 km under San Clemente Island and slopes fairly uniformly to 34 km under the San Jacinto Mountains, showing perhaps another slight rise under the San Pedro Basin. The discontinuity then rises gradually to 28.5 km under the Mojave Desert. When a model was calculated with a mantle density of 3.35 gm/cc, the depth under the ocean dropped to 12.5 km and the remainder of the model changed only slightly, deepening by 0.5 km under the San Nicolas Basin, and rising by 1 km under the San Jacinto Mountains and under the Mojave Desert.

In Model 2, the Moho drops to 12.5 km under the deep ocean, deepening to 22 km across the continental shelf, and maintaining the same depth as Model 1 under the off

shore areas and immediately inland. However, the Moho is only at 32 km under the San Jacinto Mountains, and 25.5 km under the Mojave Desert.

An attempt was made to fit a model with mantle densities of 3.40 under the oceanic areas west of the continental slope, 3.35 under the continental borderland, and 3.30 under the Mojave Desert, but no fit could be obtained. This implies that the density changes in the mantle cannot be this large, or that the upper layers would need to be more carefully considered. It could also mean that the change in density in the mantle is not particularly real, but that an anisotropic effect may be present to account for the change in seismic velocities.

The most significant disagreement with seismic data is at the continental boundary. Shor and Raitt gave a depth to the Moho under the Patton Ridge of 17.5 km. Both models in this study show a depth of at least 21km. Due to the steepness of the slope of the Moho, the depth is critically dependant on the exact point of both seismic and gravity observation; slight errors in position can lead to considerable discrepancies, which, although they seem large, are actually not significant because of the errors in position and measurement involved in the data. This discrepancy is not a significant one for these reasons.

This conclusion is in accord with Harrison et al (1966).

Another discrepancy occurs under the Santa Ana Mountains. Shor and Raitt found a depth of 32.5 km from a combination of reflection and refraction data. The reflection data indicated a possible low velocity zone; refraction data alone showed a depth of 30 km. When combined, a depth of 32.5 km was indicated. There is no indication of either the presence or absence of such a low velocity zone in the oceanic refraction data, nor is there any indication of it in the crustal studies of Roller and Healy (1963) in the area slightly to the north. The gravity model could indicate that it is not present, as there is excellent agreement with the refraction results if no low velocity layer is assumed.

Refraction work in the Mojave Desert north of Profile 1 by Roller and Healy (1963) indicated a crustal thickness of 26 km. Model 1 indicates a slightly deeper discontinuity of 28 km. Model 2, which assumes a slightly lower density under the Mojave area, indicates a depth of 25.5 km. These are both consistent with the seismic depth.

In general the agreement with seismic data for both models is rather good, and indicates a steeply sloping and possibly vertical Moho at the continental shelf, with a steady thickening inland to the San Jacinto Mountains,



and a gradual thinning under the Mojave Desert. This is in agreement with the results of Shor and Raitt (1956) and Harrison et al (1966). The only major difference revealed is the presence of the antiroot under the San Nicolas Basin. This feature would be even more prominent if a correction were made for the depth of sediments in the basin.

## PROFILE 2

The regional gradient for Profile 2 is very similar in general trend to that of Profile 1. There are three slight rises corresponding to the Santa Cruz Basin, the Santa Monica Basin, and the Transverse Ranges. The anomaly under the Mojave Desert drops to -110 mgals which is about 20 mgals lower than the minimum of Profile 1. There are again several prominent second order anomalies. The steep Bouguer anomaly across the continental margin was discussed earlier. There are three major positive anomalies associated with the shelf off the San Nicolas Island, the eastern Santa Cruz basin, and a possible basement uplift in the San Fernando Valley. There is a long broad low associated with the Santa Monica Basin, arising from the considerable depth of sedimentary fill as discussed earlier. The Mojave Desert exhibits a series of low

gravity anomalies corresponding to granitic outcrops through the sediments.

This profile corresponds to that of Roller and Healy (1963) under the land surface, and the extension into the offshore areas crosses several refraction lines of Shor and Raitt (1956). Unfortunately, little information on the deeper layers is available from these. Also, the Moho depths of Roller and Healy under the Transverse Ranges were not well established. The Moho at the coast seems to be changing rather rapidly. Roller and Healy report a depth of 29 km under the Santa Monica Bay, while Healy (1963) reports 35 km under Los Angeles and 23 km under Camp Roberts to the north of the area studied. The value of 29 km is used here; it is considered uncertain. The best seismic control points for the Moho are at the continental margin and under the Mojave desert at 26 km.

Perhaps the most interesting feature of this profile is the lack of a prominent gravity anomaly across the Transverse Ranges. One would expect that a strong regional trend would appear over a mountain mass which rises to about 3 km between two areas of little relief. The model presented by Roller and Healy indicates a considerable root under the mountains, implying a mass deficiency in the mantle and low gravity values. No such deficiency is

seen, and there is, if anything, a small mass excess present. Two models were considered in looking at this problem. Model 3 is constructed on the assumption that the Moho presented by Roller and Healy is substantially correct. A thickening of the crust to about 40 km is assumed under the Transverse Ranges, thinning to 26 km under the Mojave Desert. Under the offshore area, the crustal layer was assumed to be similar to that of Profile 1, and the resulting Moho calculated; inland, the crustal layer was calculated assuming the specified mantle depths mentioned earlier. Model 4 is constructed assuming a shallow root extending into the second crustal layer. The boundary between the two crustal layers under the Mojave is taken at 10 km based on Gutenberg (1951); this depth is probably open to question. The boundary under the oceanic areas is the same as that in Model 3. These two models represent possible extremes of the structure under the Transverse Ranges.

The resulting models and the fit to the observed gravity are shown in Fig. 10. Model 3 shows the same steep slope across the continental shelf as did the models of Profile 1. The same considerations apply. The Moho drops from 12 km under the abyssal plain to 21 km under the Patton Ridge. It slopes gradually to 23 km before

rising 3 km under the Santa Cruz basin, revealing an anti-root similar to that under the San Nicolas Basin. It drops to 24 km east of the Santa Cruz Basin and remains fairly constant until dipping sharply to the assumed 40 km under the Transverse Ranges. To satisfy the observed gravity under the assumptions made, the second crustal layer must rise sharply to 1.5 km under the mountains, drop to 11.5 km on the far side, and slope gradually to 13.5 km at the end of the profile under the Mojave Desert.

The structure indicated by this model under the ocean is probably real, particularly the presence of the antiroot under the Santa Cruz Basin. The main point of interest for the structure under the mountains is that if a root into the mantle exists, then there must be a corresponding mass increase in the crust. A structure as indicated with a very dense layer rising close to the surface should be easily detected by seismic methods; its absence would indicate no such thickening of the crust as was assumed. A density of 2.67 at a depth of 13 km is questionable; a slightly denser crustal layer would solve this problem. Alternatively, if, as in Model 2 of Profile 1, a change in mantle density were postulated under the Mojave, this would lead to a corresponding rise in the crustal interface to compensate for the decrease in mass

of the mantle. This model compares well with seismic data under the ocean; however, the depth of the Moho under the Santa Monica Bay is 3 km shallower than that indicated by seismic work. One would expect a slight antiroot under the Santa Monica Basin as was found under the Santa Cruz and San Nicolas Basins; this is not seen.

Model 4 exhibits the same Moho structure under the ocean as Model 3, showing the antiroot under the Santa Cruz Basin. However, this model shows a rise under the Santa Monica Basin of 4.5 km in contrast to the previous model. Under the assumptions made for the crustal layers, the Moho must rise by about 4 km under the mountains, dropping to about 31 km on the northern side, and gradually rise from 31 to 28 km under the Mojave. The two antiroots would be even more prominent if a geologic correction were made for the negative anomaly arising from the sediments.

This model fits the seismic data under the Santa Monica Bay, but is deeper by 4 km under the Mojave than indicated by Roller and Healy. Again, if a 3.30 density were postulated under the Mojave, the Moho would rise approximately 3 km leading to good agreement with the seismic evidence; alternatively, moving the first crustal interface down would cause a rise in the Moho. Again, the

structure of model 4 would be very easily detected by a seismic survey.

The construction of these two extreme models for the crust-mantle relationships under the Transverse ranges indicates that better knowledge of the upper crustal layers would lead to a reasonable model of the Moho. Even though seismic control is relatively good on both sides of the mountains, the interpretation of the gravity without further knowledge is completely ambiguous. Such a conclusion is not too surprising.

## SUGGESTIONS FOR FURTHER WORK

The sparsity of gravity data beyond  $120^{\circ}$  longitude makes the interpretation of the interesting continental shelf difficult. A more detailed collection of data for this area is necessary to explain the steepness of the Bouguer anomaly across the Patton Ridge and to determine the slope of the Moho at the continental margin. There is probably adequate gravity coverage of the near shore areas now, although extension of the coverage over the southern part of the Continental Borderland would be of interest.

One of the most interesting areas is the Transverse Ranges. There is no significant gravity anomaly associated with the San Gabriel and San Bernadino mountains. Whether this is due to a deep crustal root and a very near surface dense crustal layer, or to a very shallow root under the mountain and an antiroot in the Moho or some other structure cannot be answered with the present data. More detailed gravity and seismic study of these mountains is needed.

A seismic profile across the San Joaquin Hills would be useful in determining the cause of the associated gravity high.

The large negative anomaly in Santa Monica Basin

may not be due to deposition of sediments alone, but is possibly associated with downwarping of the basement without corresponding isostatic adjustment of the Moho. Comparison of this basin to the Los Angeles Basin would be of interest. A more detailed seismic and gravity survey of the basin would help in the understanding of this area.

Magnetic surveys over the entire area of study would give important additional information as to the character of the Borderland. In particular, it would help to determine if there are deep seated intrusive bodies in the areas associated with known surface volcanics, and with some of the other areas of high topography and low gravity.



## CONCLUSIONS

Gravity coverage for the northern Continental Borderland is sufficient to see the major gravity features. The regional anomaly indicates rapid thickening of the crust near the shore, with a rather constant Moho under the borderland. There are distinct antiroots under several of the offshore basins, particularly the San Nicolas and Santa Cruz basins, as shown in both the regional gravity anomaly and in the calculated crustal models. The residual gravity anomalies show distinct structural trends exhibiting a northwest-southeast trend which is terminated at the east-west trending Transverse Ranges. It also shows that some of the offshore basins have sedimentary thicknesses comparable to those deposited in the Los Angeles basin. Crustal models across the Borderland are consistent with seismic data and show an abrupt transition between the oceanic and continental margins with a rapid thickening of the Moho at the continental margin followed by gradual thickening inland and thinning under the Mojave Desert. The Transverse Ranges show no particular gravity anomaly, and the uncertainty of the seismic data leads to ambiguous interpretations of the crustal structure under the mountains.

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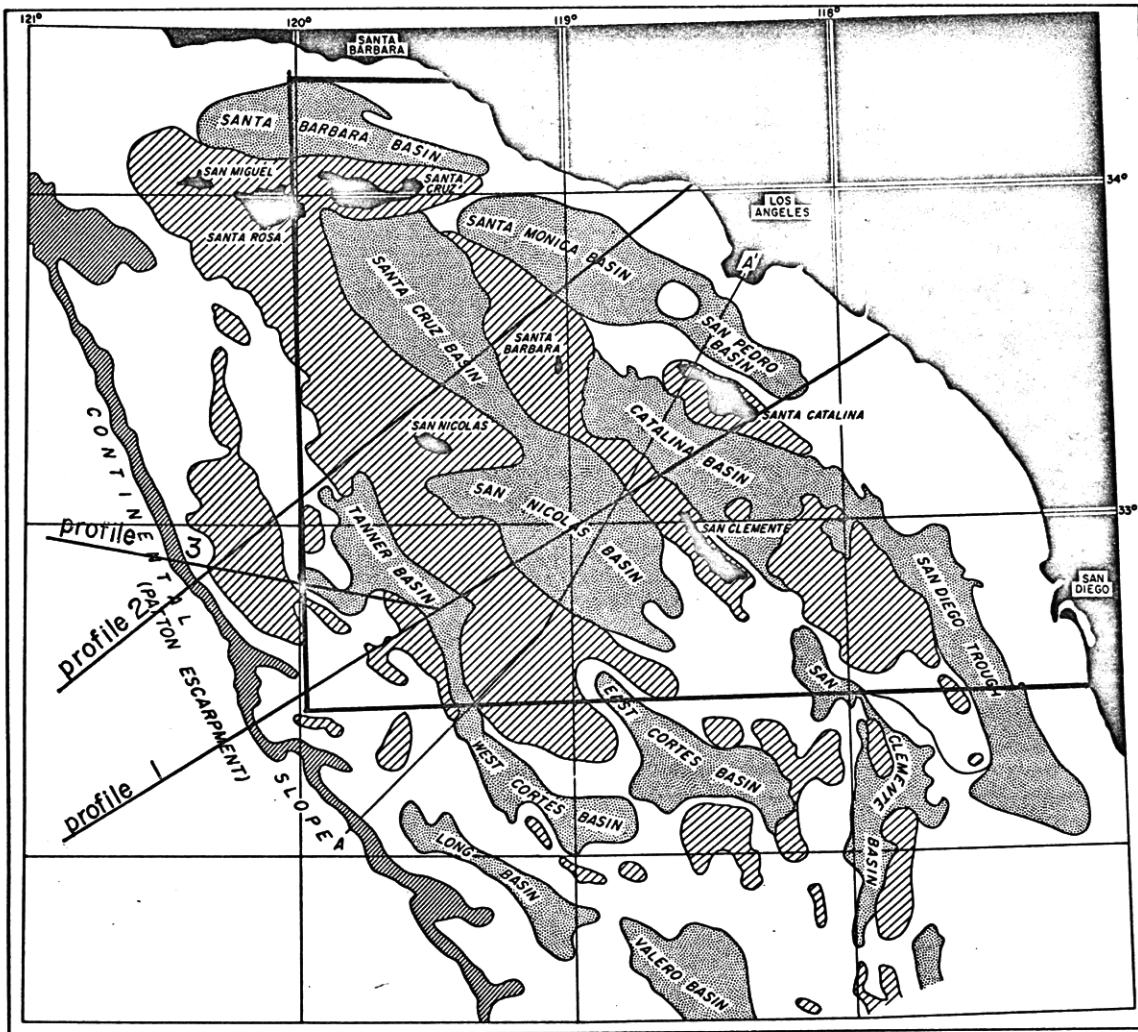
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## FIGURE CAPTIONS

- Figure 1. Approximate area of the Southern California Continental Borderland showing the major features of the sea floor. Crustal profiles are shown, and the area of Fig. 2 is outlined. Adapted from Thornbury, 1965, p. 27.
- Figure 2. Area of study, showing place names, topography, and known faults on land; from Shepard and Emery, 1941.
- Figure 3. Bouguer gravity anomalies. The numbers at the top and bottom of the map give the Bouguer anomaly plus 1000 mgals at the decimal point. Contours are based on the digits unit of the anomaly. Contour interval is 10 mgals. Blank area indicates insufficient data for contouring.
- Figure 4. Regional gravity anomalies. These are obtained by averaging the Bouguer anomalies with a 20 km radius. Anomaly values are as shown. Contour interval is 10 mgals.
- Figure 5. Residual gravity anomalies, obtained by subtracting the regional anomaly from the Bouguer anomaly. Some values are shown; the range is -50 to +50 mgals. Contouring was based on units digit of the residual anomaly plus 1000 mgals similar to the Bouguer map; thus areas contoured with a 7 are actually -30 mgals. Similarly,

a 3 implies +30 mgals.

- Figure 6. Areas of high and low residual gravity taken from figure 5. This shows possible structural blocks.
- Figure 7. Bouguer and regional gravity anomalies and topography for Profile 1. Major features are indicated.
- Figure 8. Proposed crustal models for Profile 1. The solid circles on the models indicate seismic control points. The calculated gravity is shown by open circles for Model 1, open squares for Model 2, and closed circles if the points coincide. Observed regional anomaly is shown as a solid line.
- Figure 9. Bouguer and regional gravity anomalies and topography for Profile 2. Major features are indicated.
- Figure 10. Proposed crustal models for Profile 2. Calculated gravity is shown by square or circle as indicated; observed gravity is shown as a solid line. Closed circles on models represent seismic control points; the question mark indicates uncertain seismic control.



EXPLANATION

- Troughs or Basins
- Intermediate topography
- Ridges or Banks
- Patton Escarpment

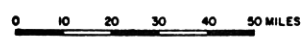


FIG. 1







FIG 3

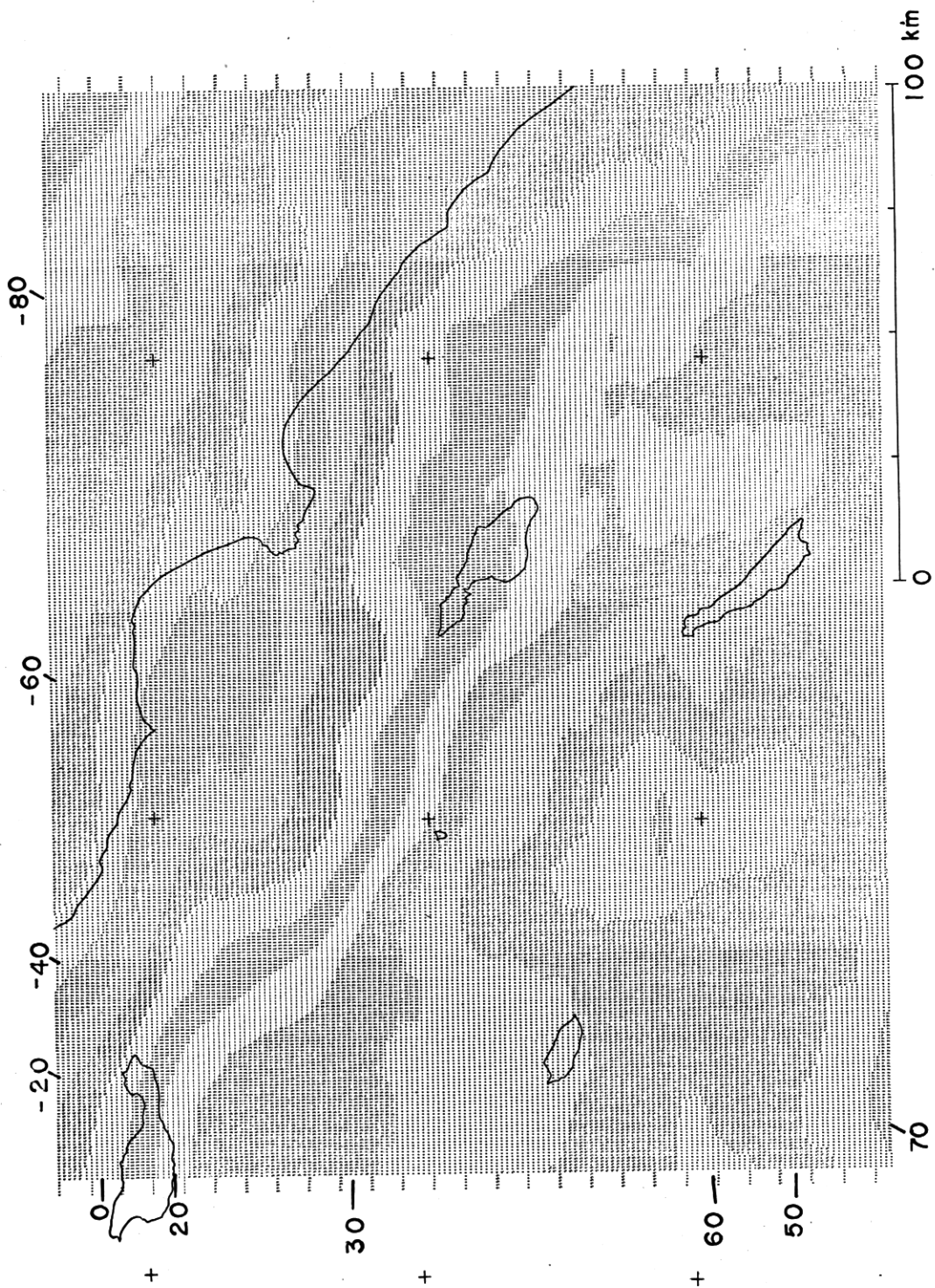
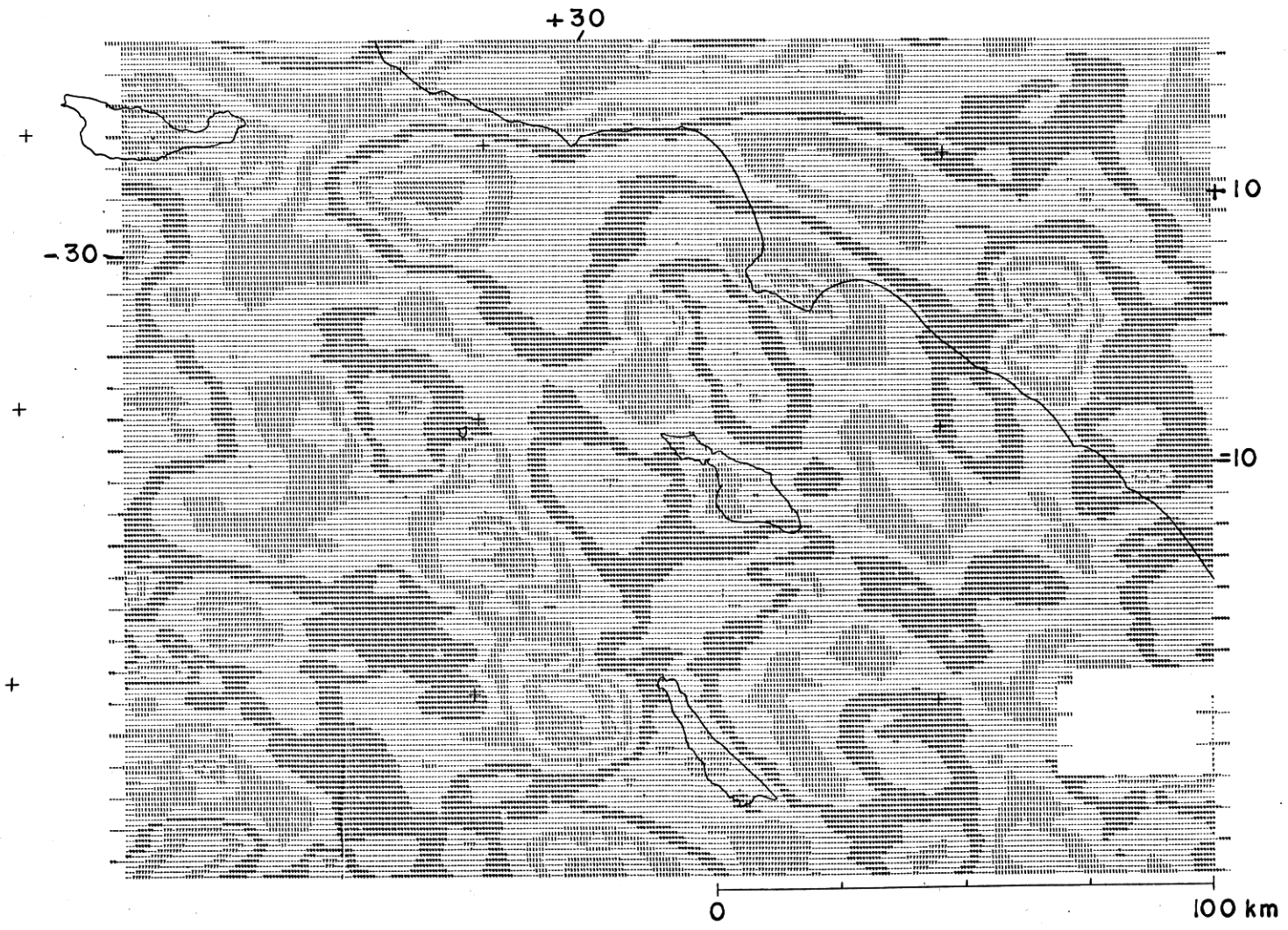


FIG 4



FIG 5





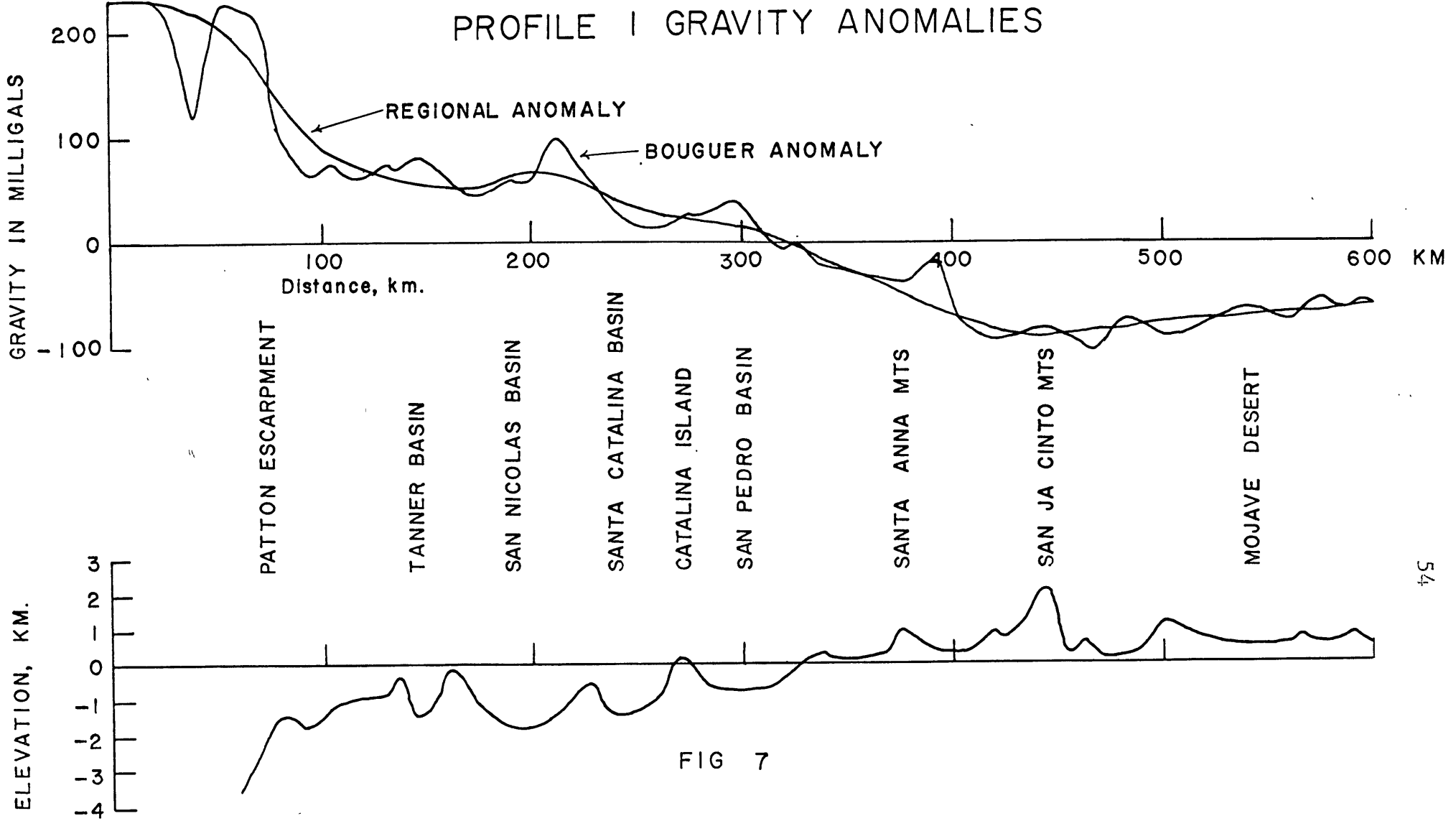
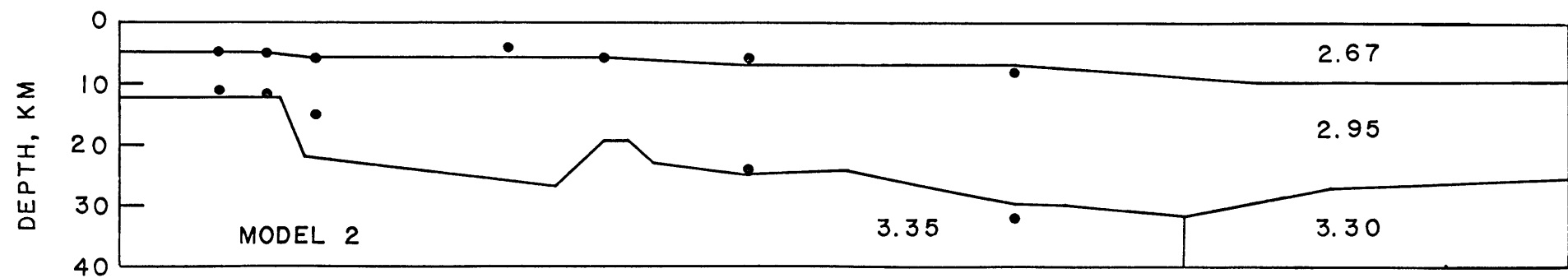
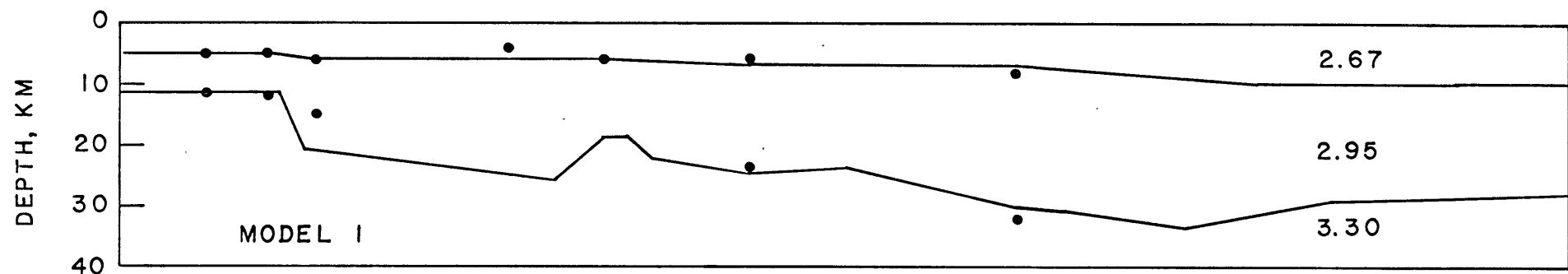
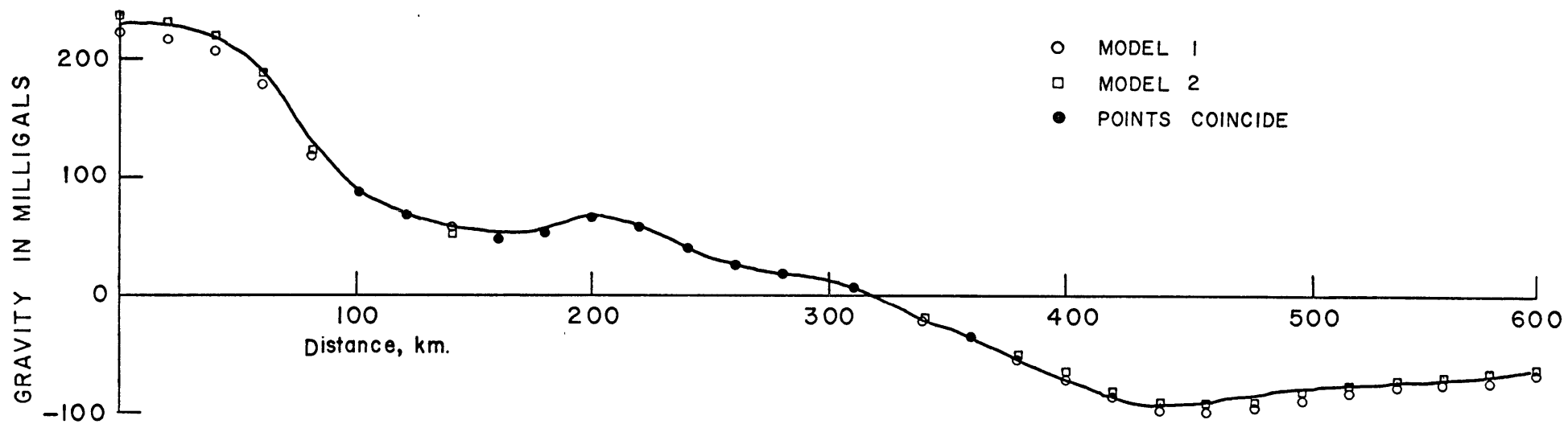
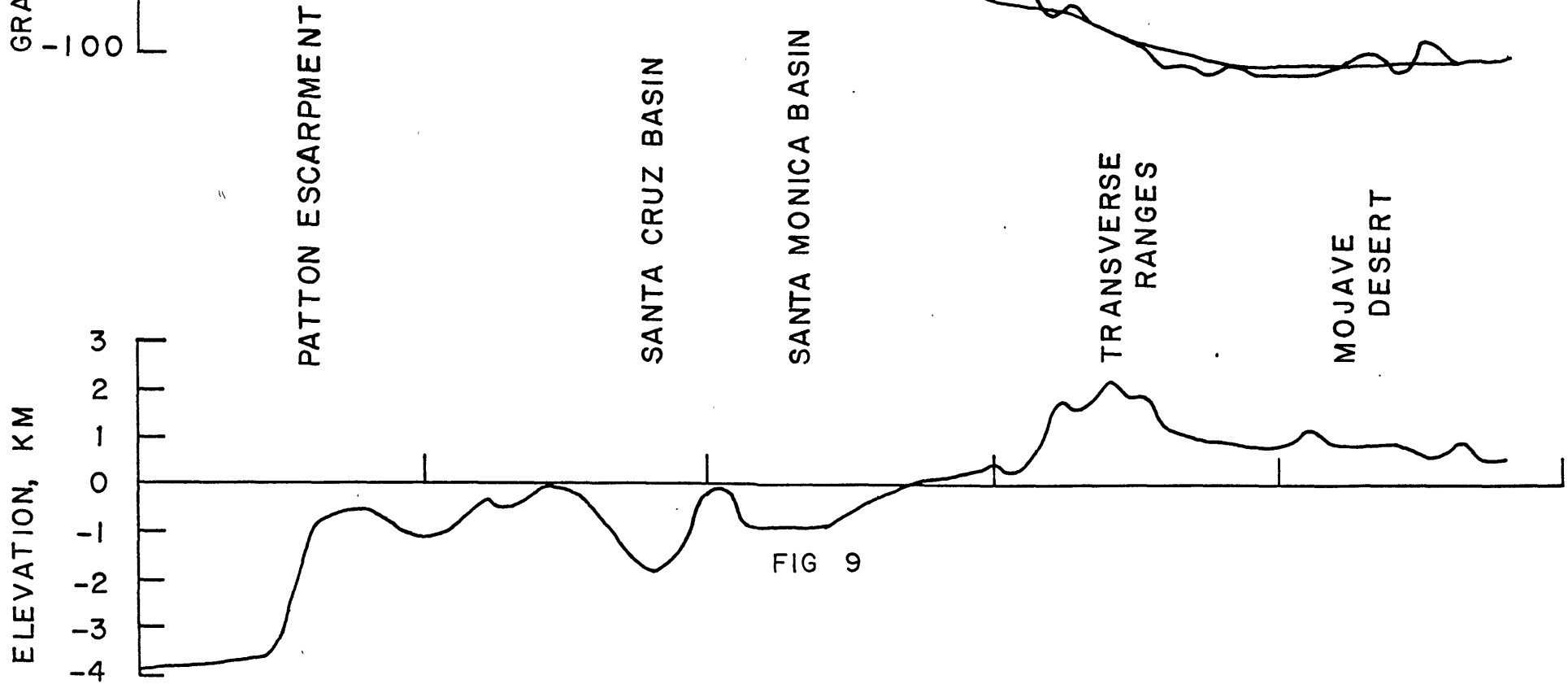
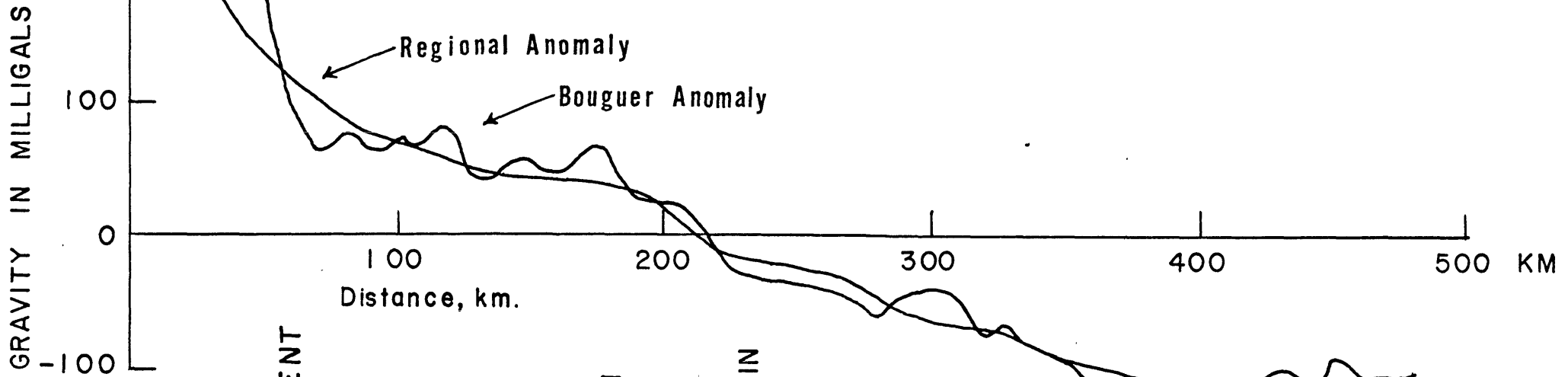


FIG 7



# PROFILE 2 GRAVITY ANOMALIES



PATTON ESCARPMENT

SANTA CRUZ BASIN

SANTA MONICA BASIN

TRANSVERSE RANGES

MOJAVE DESERT

FIG 9



